An integrated assessment of hemp (*Cannabis sativa* L.) and flax (*Linum usitatissimum* L.) as sources of fibre for newsprint production.

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A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

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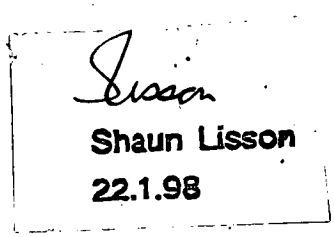

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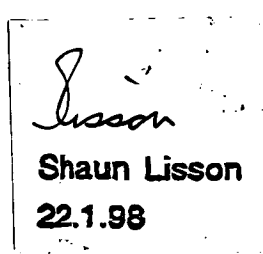

Table of contents.

Section V: Utilisation of fibre hemp and flax as a source of pulp for newsprint production in Tasmania

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Summary:

The primary objective of the study reported in this thesis was to show whether fibre of value as a reinforcing agent in newsprint production could be produced economically from hemp and flax grown in Tasmania. This involved an integrated analysis of the whole potential industry, with studies into the key areas of crop production, pulp and paper manufacture and economic viability. Another objective of the study was to develop a computer model for simulating the growth, development and yield of hemp in response to climatic, soil and management inputs. This would enable the results of this project to be extrapolated to other suitable production areas and hence assist in the initial assessment of cropping potential and the identification of optimum site and management conditions.

Of the nine hemp cultivars that were assessed, Kompolti and Futura 77 were the best performing, producing crops in excess of 2 m high and yielding up to 1500 g/m^2 of oven dry stem. The results from sowing date trials suggest that September is the optimum month for sowing hemp in Tasmania. Later sowings resulted in a reduction in stem yield associated with a shortening of the thermal time duration from sowing to flowering. Furthermore, van der Werf *et al.* (1996) reported yield declines from later sowings due to delays in canopy closure and a subsequent reduction in intercepted radiation. Sowings prior to September appear to be limited by premature flowering in response to short daylengths. In an irrigation trial conducted in north west Tasmania, significant stem yield differences were not apparent for irrigation regimes based on refill to field capacity at deficits down to 120 mm. Maximum bark yield was obtained from regimes based on a 60 mm deficit or less (water consumption of 535 mm). The stem yields under rainfed conditions were substantially below those of the irrigated treatments. Stem yield responded in a parabolic manner to plant densities ranging from 50 to 300 plants/m^2, with maximum yields at about 110 plants/m^2.

The results from a flax cultivar trial showed that stem yields of selected European cultivars were superior to a number of older Australian cultivars, developed for the Australian flax industry during the mid 1900's. The cultivar Ariane was selected for further field trials and produced crops with oven dry stem yields of up to 1000 g/m^2. Field studies with a range of sowing date and irrigation treatments demonstrated that flax could be sown from autumn through to spring, under either rainfed or irrigated conditions. Maximum stem and seed yields were from an autumn sowing with supplementary irrigation from flowering to late grain fill. The optimum seeding

rate for autumn sown flax was found to involve a compromise between maximising yield and minimising the potential losses from lodging apparent at densities in excess of about 1000 plants/m^2. Lodging was not a major problem at the optimum seeding rates for spring sowings of flax.

Controlled environment studies were conducted into the response of pre-emergent development to temperature, and the flowering response of selected hemp cultivars to photoperiod. Parameters, constants and functions derived from these studies, the field trials and from selected references, were then used to develop a hemp simulation model. The model adequately predicted phenology, leaf area and biomass production for cv. Kompolti grown in north west Tasmania.

The Australian newsprint industry currently uses a mixture of locally sourced eucalypt, radiata pine and recycled paper pulps, blended with an imported kraft (chemical) pulp. The purpose of the kraft pulp is to reinforce the newsprint. The primary aim of the pulping trials conducted in this study was to investigate the potential of using flax and hemp bark and whole stem pulps as alternative reinforcing agents in newsprint production. The existing cold caustic soda (CCS) and thermomechanical (TMP) processes were trialled with a view to harnessing the existing infrastructure and expertise. Cold caustic soda pulp made from the bark fraction formed paper of very high tear index, but with lower tensile index and tensile energy absorption than would be desirable from softwood kraft. This limitation might be overcome by using a higher proportion of non-wood pulp in the overall newsprint blend or through breeding improvements. The use of pulping (& pre-pulping) equipment more suited to non-woods may overcome handling difficulties associated with excessive fibre length.

Pulps were also made from the core fraction to assess its suitability as a supplement to the short fibred component of the existing newsprint blend. Whilst potentially suited for use as a short fibred supplement in newsprint manufacture, the properties of the core pulps are not currently in demand within the industry.

Interest from the newsprint industry in taking the financial risk of adopting hemp and flax based pulps as an alternative to kraft, would require that the total cost be somewhat less than the imported option. Similarly, interest from primary producers

requires that the gross returns from these crops are at least comparable with a range of crop alternatives. The minimum bark price (mill gate) that is likely to attract farmers would vary between flax and hemp and between growing conditions. Dual purpose flax grown under dryland conditions would require a separated bark price in the vicinity of $400/t to $450/t. Irrigated hemp and flax crops grown in the more productive north west area of the state would require a price in excess of about $650/t. These minimum bark prices are not attractive to the newsprint industry at present. Future financial viability will depend on a number of factors, including: fibre yield and quality (eg bark proportion in the stem and fibre tensile strength properties) improvements, elevated kraft pulp prices, and the establishment of strong markets for the stem core fraction and the seed of flax.

Section I: Introduction:

I.1 Background:

The first exploratory licence to grow fibre hemp in Tasmania was issued by the State Government in December 1991, following concerted lobbying by a local interest group known as the Tasmanian Hemp Company. Due to delays in licence issue, this first crop was sown too late and submissions were immediately made for a second licence to be issued for the 1992-1993 season. This crop proved successful with promising dry stem yields of the order of 8 t/ha.

Growing interest in the papermaking potential of hemp led to preliminary laboratory pulping trials by the Tasmanian based operation of Australian Newsprint Mills Ltd. (ANM) in 1993. Of primary interest was the possible replacement of kraft pulp, currently used by the mill as a reinforcing agent in newsprint manufacture. Approximately 20000 t of kraft pulp is imported each year from New Zealand, the United States of America and Canada. The other components of ANM's pulp blend are sourced either locally (eucalypt and radiata pine) or from mainland Australia (recycled fibre). It was thought that hemp had the potential to provide a locally sourced alternative to kraft, offering the company advantages in terms of far greater control over price and supply. Hemp has traditionally been used in the manufacture of high strength grades of paper. Furthermore, recent research in the Netherlands (van Roekel *et al.* 1995) indicated the possibility of producing a pulp with comparable properties to chemical softwood pulp, using mechanical and chemimechanical processes. These findings were particularly interesting to ANM, given their preference for using processes similar to those currently in operation at the mill, notably the cold caustic soda (CCS, chemimechanical) pulping of eucalypt and the thermomechanical pulping (TMP) of pine. This would enable them to harness their expertise in mechanical pulping and possibly utilise the existing mill infrastructure.

On the basis of the above findings, a jointly funded, co-operative study between the University of Tasmania's Department of Agricultural Science and ANM was proposed in late 1993. The study, which forms the basis of this thesis, commenced in early 1994.

I.2 Study objectives:

The primary objective of the study was to show whether fibre of value as a reinforcing agent in newsprint production, could be produced economically from hemp and flax grown in Tasmania. This involved an integrated analysis of the whole potential industry, with studies into the key areas of crop production, pulp and paper manufacture and economic viability. Flax was considered as a dual purpose crop grown primarily for fibre, with seed as a potentially valuable by-product (Anonymous 1992). Hemp was considered as a single purpose crop grown for fibre only.

The decision to expand the study to include flax was based on a number of considerations. Firstly, the fibres of flax and hemp have similar properties and are used interchangeably in the manufacture of specialty papers (Wong & Chiu 1995). Both crops are potentially suited to the temperate climatic conditions of Tasmania. Furthermore, the cultural requirements of each species are quite different and as such, complement each other in their suitability for different land types and agricultural practices. This would enable fibre production over a wider area of the state and enable sufficient production to meet the supply needs of ANM.

The second objective of the study was to develop a computer model for simulating the growth, development and yield of hemp in response to climatic, soil and management inputs. The impetus for this arose from the growing interest in hemp cultivation in Australia. It was felt that a model for hemp would be a particularly useful tool for both the initial assessment of cropping potential and later, for identifying optimum site and management conditions. The value of a hemp simulation model is further enhanced by the political, social and security problems and restrictions associated with hemp cultivation.

I.3 Hemp botany and crop description:

Fibre hemp is a summer grown, herbaceous annual. Hemp plants grown for fibre are generally unbranched and may reach heights of up to 4 m (Figure I.1.1-2). Leaves are palmately lobed with a variable number of leaflets depending on the nodal position. Phyllotaxis shifts from opposite to alternate shortly after flowering. Hemp is naturally dioecious, however monoecious varieties have been bred and are widely cultivated throughout Europe (Figure II.1.1). Hemp is a short day plant

Figure I.1: (1) Hemp (1994-95 sowing date X cultivar) trial showing the crop at ~4 weeks, 7 weeks, 9 weeks and 11 weeks after sowing. (2) Hemp cultivar Kompolti at flowering. (3) Hemp stem broken and teased to show the two fractions of bark and core.

with flowering accelerated by short days (Heslop Harrison & Heslop Harrison 1969). The male inflorescence is a terminal or axillary panicle bearing flowers with five perianth members and five stamens. Female flowers are sessile and occur in pairs, with each flower surrounded by a bract and consisting of five perianth members and two styles.

The stem of both hemp and flax can be divided into two components: the bark fraction (outside the vascular cambium) and the core fraction (inside the vascular cambium) (Figure I.1.3). The bark fraction of hemp contains primary bast fibres and may also contain secondary bast fibres. Primary bast fibres vary from 3-55 mm in length and are approximately 34 μm in diameter. Secondary bast fibres have a mean length of 2 mm and a width of 17 μm (Kundu 1942, Catling & Grayson 1982, as cited by van der Werf 1994). The core fraction contains much shorter fibres; 0.5-0.6 mm long by about 25 μm wide (Bosia 1976, as cited by van der Werf 1994).

Fibre hemp contains low levels of psychoactive resins, primarily delta-9-tetrahydrocannabinol (THC). Despite these low levels, no legal distinction is made between fibre varieties and the more infamous drug varieties. In Tasmania, *Cannabis sativa* is a prohibited plant under the Poisons Act of 1971 (Section 52) and hence trial cultivation required special licences, issued and administered by the Tasmanian Government Departments of Justice and Health. These licences specified the terms and conditions relating to crop security, access, harvesting, disposal, maximum allowable THC content (0.35% w/w dry weight) and THC testing procedures.

The crop is grown both for its seed and fibre, either as separate single purpose crops or as a dual purpose crop. In a review of literature relating to harvest timing, van der Werf (1991) reports that single purpose fibre hemp crops are usually harvested at about the end of female flowering, when stem growth is complete and prior to the lignification of bast fibres that occurs during seed set (Heuser 1927, as cited by van der Werf 1991). The harvesting system for fibre hemp usually begins with the cutting of the crop using a mower/conditioner or windrower. The straw is then left and occasionally turned to promote uniform and quick drying and retting. Once the moisture content drops to about 15%, the straw is baled and collected for off-farm processing. The development of mobile decorticating units to separate the

core and bark fractions of hemp offer the possibility of field based processing (Graham 1995). Harvesting of the dual purpose crop begins with the cutting and threshing of the upper seed bearing portion of the plant. The remaining straw is harvested as for the fibre only crop (Maeyer & Huisman 1994).

It was initially felt that seed might be a potentially valuable by-product from the fibre hemp crop grown in Tasmania. However, dual purpose cropping was discounted early on the basis of observations from a preliminary harvesting trial conducted at Cambridge in the 1994-95 season (Chapter II.5). These studies concluded that dual purpose cropping of hemp was not conducive to optimising fibre yield and quality and that it would be better to grow separate seed and fibre crops.

I.4 Flax botany and crop description:

Flax and linseed cultivars both belong to the *Linum usitatissimum* species. Linseed varieties are bred and grown for high seed yields, whereas flax varieties are bred and grown for fibre yield and quality. Consequently, flax tends to be taller, carries fewer flowers and yields less seed than linseed. There are also dual purpose cultivars grown both for seed and fibre.

Flax is an erect annual, grown either as a spring or autumn sown crop in cool temperate regions (Figure I.2.2-5). Individual flax plants have a single glabrous, greyish green stem of approximately 2-4 mm diameter at the base and up to 1.2 m in length. The root system consists of a main tap with subsequent branching to a depth of up to 1.5 m under ideal conditions. Limited branching occurs at the top of the main stem, producing short stems terminated by the flowers. Leaves are lanceolate, small, entire and glabrous grey-green. Flowers open shortly after dawn with predominantly self pollination occurring by mid morning (Figure I.2.3). The petals fall shortly after, with complete loss by about noon of the same day. The ovaries ripen to produce globular capsules containing five carpels, each with individual loculi for two seeds. Seed maturity occurs 30-60 days after final bloom. Flax crops grown just for fibre are usually harvested between green and brown capsule stages (growth stage 10-11, Turner 1987) when the fibres have reached optimum development. Dual purpose crops are left to proceed through to seed ripeness (growth stage 12, Turner 1987) when the seeds can be heard to rattle in the capsules.

Figure I.2: (1) Seed of the flax cultivar Ariane (a), the linseed cultivar Linola (b) and the hemp cultivar Kompolti (c). (2) Flax (1996-97 irrigation X sowing date X seeding rate) trial showing the crop at various stages of development.
(3) Commencement of flowering in Ariane (Growth stage 7-8, Turner 1987).

Figure I.2 (cont): (4) Mature capsules (bolls) of Ariane. (5) Mature plants of Ariane at height of ~1.2 m.

The bark fraction of the flax stem contains only primary bast fibres with lengths ranging from 2-40 mm and diameters from 20-23 μm (McDougall *et al.* 1993). Core fibres have a mean length of 0.5 mm and a mean diameter of 16 μm (Zhang & Nie 1992).

In Europe, flax harvesting employs specialised machinery and begins with the crop being pulled and the capsules removed (rippled) from the straw. The straw is left in the field to dry (and ret) and is then either baled and transported to a separate processing facility, or field decorticated and the bark fraction baled in one pass. The capsules removed during rippling are taken away to be dried and the seed then removed by threshing. New harvesters are being developed by the harvesting machinery company, Claas, which cut, thresh, decorticate and bale the bark fibres in one pass (Turner 1987, Anonymous 1994).

I.5 Thesis structure:

This project was designed to answer the following questions:

1) What are the potential fibre yields from flax and hemp grown in Tasmania?.

2) How can genotypic and cultural factors be manipulated to produce these potential yields?.

3) Can a model be developed to simulate the growth and development and hence yield of hemp?.

4) Can the stem fibre of these crops be used to replace imported kraft pulp to make a satisfactory paper at a competitive price?.

No comprehensive agronomic field trials have previously been conducted in Australia with fibre hemp. However, in the case of flax, field studies were conducted in Tasmania during the Second World War when the crop was grown commercially for textile and rope manufacture (Tilt 1941, Wilson 1944, Hansen 1945). Whilst providing some useful information, there was clearly a need for fresh and more extensive agronomic studies. Selected areas of study for the two crops included the screening of selected cultivars and the investigation of responses to sowing date, plant density and irrigation. Preliminary trials were also performed to investigate suitable equipment and methods for harvesting hemp. The findings of these studies are reported in Sections II and III of the thesis.

The development of the model is addressed in Section IV. Chapter IV.1 reports on the effect of temperature on pre-emergent growth. Chapter IV.2 reports on the flowering response of selected hemp cultivars to photoperiod, based on controlled environment studies. Chapter IV.3 reports on the effect of plant density on leaf area production. Parameters and constants developed from these preliminary studies are then used in the development of the hemp simulation model described in Chapter IV.4.

Section V reports on the laboratory pulping and papermaking trials with hemp and flax. The primary aim of the pulping trials was to investigate the potential of using flax and hemp bark and whole stem pulps as alternative reinforcing agents in newsprint production. Pulps were also made from the core fraction to assess its suitability as a supplement to the short fibred eucalypt component of the existing newsprint blend.

Section VI considers the economic viability of hemp and flax production for use as a reinforcing agent in newsprint manufacture. Crop budgets were prepared from likely production yield, cost and price estimates. Sensitivity analyses were also prepared to examine the effect of fluctuations in these parameters on economic returns. Comparisons were made with existing crop options in the Tasmanian farming sector.

Section II: Hemp agronomy studies.

II.1 Evaluation of selected fibre hemp cultivars.

II.1.1 Introduction:

The purpose of this trial was to import a number of selected European fibre hemp cultivars and rank their performance under Tasmanian growing conditions. The most highly ranked cultivar from these trials was used in further crop production and physiology studies.

Cultivar selection was based on the following three criteria.
a) Cultivation licences issued by the Tasmanian Government require that the THC level in any part of the plant not exceed 0.35% (dry weight basis). Most commercially available fibre cultivars do not exceed this value. However, there were at least two promising cultivars which had to be excluded on the basis that their THC levels were in excess of this limit.

b) Preference was given to cultivars with a high proportion of bark fibre in the stem fraction. This fibre is of primary interest to Australian Newsprint Mills Ltd. as a reinforcing agent in their papermaking process. In a comprehensive evaluation of 160 *Cannabis* accessions by Meijer (1994), the total bark fibre fraction was found to range from 9 to 34%.

c) As part of the same study into diversity in *Cannabis*, a positive relationship was found between day of anthesis and yield potential (Meiijer & Keizer 1994). Hence, selected cultivars should flower as late as possible under Tasmanian conditions.

With these criteria in mind, a list of potentially suitable cultivars was made. Problems with seed availability meant that just nine of the preferred cultivars were eventually imported for screening. These included three from the Ukraine (USO 11, USO 14 and USO 13), four from France (Futura 77, Felina 34, Fedrina 74 and Ferimon 12), and two from Hungary (Kompolti and Unico B).

USO 11, USO 14 and USO 13 were developed at the Institute of Bast Crops of Ukrainian Academy of Agrarian Sciences (Meijer 1995). All three are monoecious in their flowering habit. P. Goloborodko (pers. comm. 1995) ranked USO 14 as the earliest flowering and USO 13 as the latest flowering of the three cultivars .

The Hungarian cultivars were bred at the GATE - "Rudolf Fleischmann" Agricultural Research Institute in Kompolt. Kompolti is a selection from Italian hemp landraces. Unico-B is the F2 of a hybrid F1 of Kompolti and Fibrimon 21, a selection from a monoecious cross-bred cultivar with high fibre content (Bosca 1995). Both Kompolti and Unico-B are dioecious (Figure II.1.1.1).

The four monoecious French cultivars were bred at the Federation Nationale des Producteurs de Chanvre in Le Mans (Figure II.1.1.2). Ferimon 12 is a selection from Fibrimon 21. The remaining cultivars are from cross-progenies of Fibrimon selections and various dioecious fibre strains. The higher the number added to the name of the cultivar, the later the flowering (Meijer 1995).

II.1.2 Materials and method:

Design:

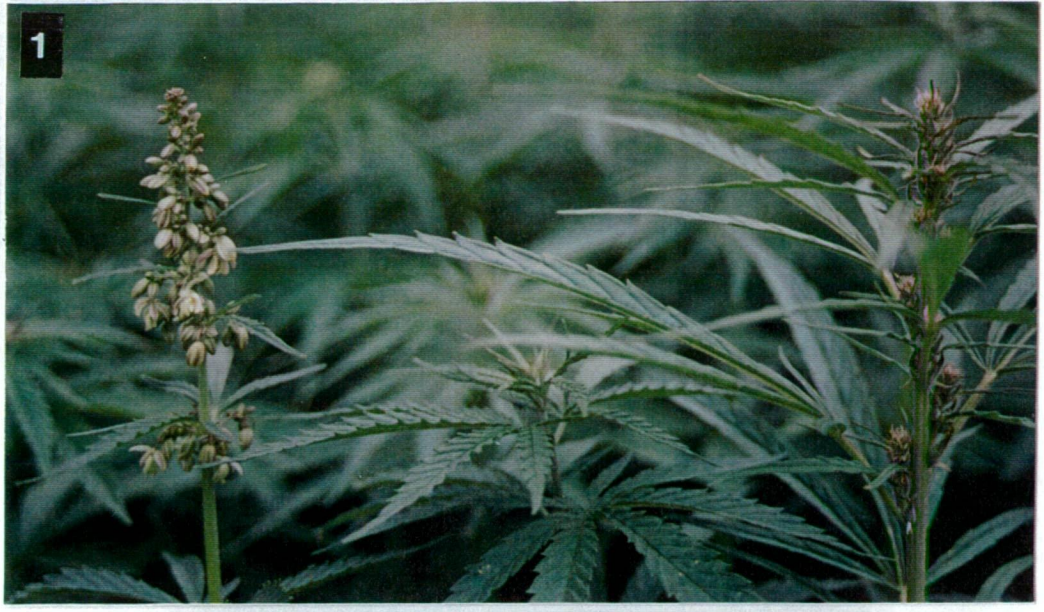
Delayed seed arrival and poor seed quality meant that cultivar screening had to be spread over two seasons. Security concerns with the first trial conducted at the University of Tasmania Farm at Cambridge (42°50'S, 147°30'E), required the second trial to be shifted to a more secure site at the Forthside Research Station (41°10' S, 146°40'E). Fedrina 74, Felina 34, USO 11 and Unico B were trialled at Cambridge. USO 13, USO 14, Futura 77 and Ferimon 12 were trialled at Forthside. Kompolti was included as a benchmark in each trial.

At each site, a randomised complete block design was employed with four replicates. Each plot was 5 m long X 1.5 m wide. A buffer zone of one plot width (cv. Kompolti) was sown on either side of the trial area to minimise edge effect.

Cultural methods:

Seed was sown to a depth of approximately 3-4 cm using a 10 row cone seeder with 15 cm row spacings and 1.8 m plot centres. The target plant density was 200 plants/m^2.

The Cambridge trial was sown on October 13, 1994 and the Forthside trial on October 17, 1995.



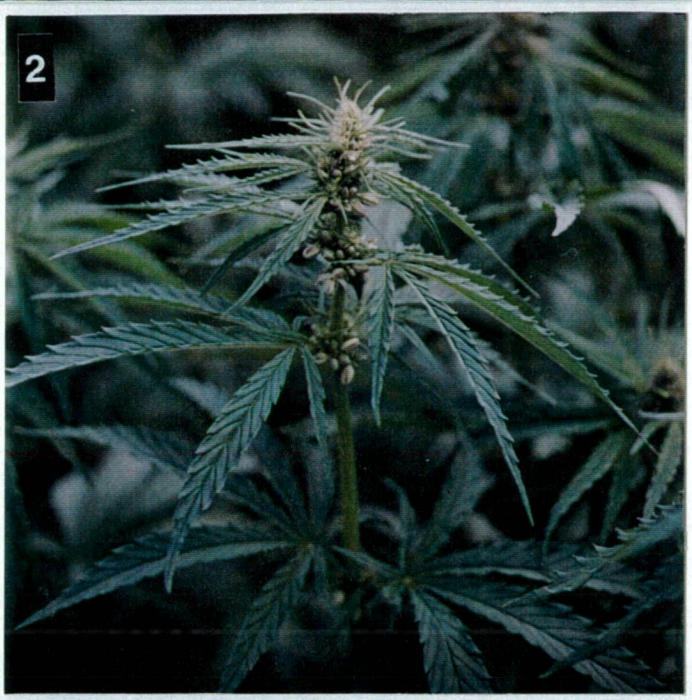


Figure II.1.1: (1) Male (left) and female (right) plants of the dioecious cultivar Kompolti. (2) Hermaphrodite plant of Futura 77. (3) Plots of USO 13 (a) and Futura 77 (b) in the cultivar trial at Forthside. USO 13 has already flowered and clearly has a lower stem yield potential than Futura 77, which is yet to flower.

Fertiliser application was based on soil test results and target soil reserves of 100 kg/ha N, 40 kg/ha P and 100 kg/ha K. Composite fertiliser with an N:P:K ratio of 9:14:17 was predrilled at both sites; 300 kg/ha at Cambridge and 350 kg/ha at Forthside. This was followed by a topdressing of nitrogen fertiliser at 40 kg N/ha shortly after emergence. Low zinc levels at Forthside necessitated an application of zinc sulphite monohydrate at a rate of 30 kg/ha.

The Cambridge trial was irrigated with overhead sprinklers on nine occasions (~30 mm per application) from early November to early February. Sprinklers were also used at Forthside, with scheduling based on a cumulative deficit of 35 mm measured with a 'Class A' pan evaporimeter.

The trial areas were hand weeded on one occasion prior to complete ground cover. Thereafter, weed growth was adequately suppressed by the hemp crop.

To counter the loss of newly emerged seedlings by birds at Cambridge, bird control tape and hawk effigies were set up about the trial area.

Data collection and analysis:

The initial trial at Cambridge was allowed to proceed through to seed maturity with a view to assessing the dual purpose seed/fibre potential of the cultivars. Security problems during this first season led to a requirement by government authorities that subsequent trials be harvested at flowering. As a consequence, only vegetative yield comparisons were possible in the second trial at Forthside.

The date of flowering was determined from regular observations of plants within each treatment. Flowering was taken as the time when 50% of plants had one or more pedicillate male flowers or stigmatic female flowers visible to the naked eye. This method is based on an approach used by van der Werf *et al.* (1994).

At final harvest, all above ground plant material apart from senesced leaf matter and severely suppressed living plants (a result of 'self thinning') was collected from within a sample area of 2 m^2 from each plot. The total fresh weight and plant density were derived from this sample. A random selection of 20 plants was then set aside for partition analysis and measurement of stem dimensions. Stem length

was measured from ground level to the top of the fruiting zone. Diameter was measured at the base of the stem. The plants were then manually partitioned into stem, leaf and reproductive fractions and oven dried at 70 °C for 48 hours for dry matter and yield determination.

At final harvest, the proportion of bark in the stem was determined from stem sections. Starting from about 15 cm above ground level, sections of approximately 30 cm in length were taken from 15 individual female or monoecious plants from each plot. The bark was peeled away from the core by hand and the relative proportions calculated from oven dry weights of each separated fraction.

THC (delta-9-tetrahydrocannabinol) and CBD (cannabidiol) percentages were determined by the Tasmanian Government Analytical Laboratories using gas chromatography. Cumulative samples of flowering heads were collected shortly after the commencement of flowering from 20 individual female or hermaphrodite plants (5 per replicate) within each cultivar population. This sample size is reported by Meijer *et al.* (1992), to provide a reliable approximation of the average THC content.

Analysis of variance tests were performed on total dry matter, yield, yield components and stem dimensions using Systat 5.2.1 software. Means were compared using the Fisher LSD test with significance for P values less than 0.05.

II.1.3 Results:

Yield, stem dimension and plant density results for the two trials are shown in Table II.1.1. Results for Felina 34, USO 13 and USO 14 are not included due to poor establishment.

Plant density at harvest:

Substantial variation in plant density at harvest was apparent both within and between treatments in the Cambridge trial. This is attributed to the damage caused by birds shortly after emergence. The low germination percentage associated with Unico B further contributed to the significantly smaller ($P<0.05$) population recorded for this cultivar.

The poor establishment of Felina 34, USO 13 and USO 14 treatments was attributed to poor seed quality and prevented meaningful yield assessment of these cultivars. However, sufficient plants were available to observe flowering time (Table II.1.2), a useful indicator of stem yield (Meijer & Keizer 1994) (Figure II.1.1.3).

Table II.1.1: Final harvest results for the hemp cultivar trials at (a) Cambridge and (b) Forthside. Fisher LSD figures shown with extent of significance of analysis of variance ie *P<0.05, **P<0.01, ***P<0.001, n.s. not significant.

(a) Cambridge Trial:

	Cultivar:				
	Unico B	Kompolti	Fedrina 74	USO 11	LSD 0.05
Plant density (/m²)	63	126	140	144	73***
TDM (g/m²)	1591	1303	1166	1172	n.s
Stem yield (g/m²)	1357	1174	893	868	217*
% Bark	35.2	37.4	32.8	34.6	2.4*
Seed (g/m²)	135	43	84	100	41*
Stem length (cm)	226	191	179	140	12***
Stem diameter (mm)	12.2	8.7	7.4	7.8	1.5***

(b) Forthside Trial:

	Cultivar:			
	Kompolti	Futura 77	Ferimon 12	LSD 0.05
Plant density (/m²)	148	106	125	23*
TDM (g/m²)	1386	1361	1129	147*
Stem yield (g/m²)	1190	1141	894	88**
% Bark	39.9	37.1	38.5	2 *
Stem length (cm)	209	195	174	15*
Stem diameter (mm)	10.6	8.5	6.8	1.5**

Total dry matter, yield and bark percentage:

Significant differences were apparent for stem yield in both trials. In the Cambridge trial, the stem yields of Unico B and Kompolti were significantly greater than Fedrina 74 and USO 11. At Forthside, Kompolti and Futura 77 were superior in stem yield to Ferimon 12.

Similar trends were apparent for total dry matter. At Cambridge however, significant differences were masked by large within treatment variability.

The highest proportion of bark was found in Kompolti and Ferimon 12 at Forthside, and in Kompolti at Cambridge.

The large seed yield of Unico B reflects the extensive branching associated with the low plant densities of this cultivar. Of the remaining three cultivars, the monoecious plants of USO 11 and Fedrina 74 yielded significantly more seed than the dioecious Kompolti.

Stem dimensions:

The significantly larger stem dimensions of Unico B relative to the other cultivars trialled at Cambridge, is a response to the lower plant densities for this cultivar (see Chapter II.3). Of the other cultivars in this trial, Kompolti had the longest stem length, followed by Fedrina 74 and finally USO 11. A positive relationship between stem length and yield potential has previously been reported by Meijer & Keizer (1994). Differences between the stem diameter of cultivars trialled at Cambridge were not significant.

At Forthside, Futura 77 and Kompolti had longer and thicker stems than Ferimon 12. The stems of Kompolti were thicker than those of Futura 77.

Flowering:

Table II.1.2: Date of flowering, days from sowing to flowering, %THC and %CBD for the (a) Cambridge and (b) Forthside hemp cultivar trials.

(a) Cambridge Trial:					
	Cultivar:				
	Unico B	Kompolti	Fedrina 74	USO 11	Felina 34
Flowering date	23.1.95	26.1.95	8.1.95	5.12.94	20.12.94
Days to flowering	103	106	88	54	69
% THC	0.03	< 0.01	0.11	0.01	0.14
% CBD	0.15	0.24	0.72	0.14	0.89
(b) Forthside Trial:					
	Cultivar:				
	Kompolti	Futura 77	Ferimon 12	USO 13	USO 14
Flowering date	25.1.96	20.1.96	24.12.95	10.12.95	1.12.95
Days to flowering	101	96	69	55	46
% THC	0.22	0.22	0.26	0.07	0.01
% CBD	0.97	0.9	0.97	0.56	0.17

Stem yield tended to increase with later flowering (Table II.1.2). The ranking among French and Ukrainian cultivars for days to flowering is similar to that reported by Meijer (1995) and Goloborodko (pers. comm. 1995).

The three cultivars for which yield data could not be measured (Felina 34, USO 13, USO 14) flowered in early December. On the basis of these early flowering dates, it could be expected that stem yields would have been low (Meijer & Keizer 1994).

THC levels:
THC levels were consistently below the legal maximum of 0.35% (Table II.1.2).

There was considerable variation in the psychoactivity of Kompolti between the two trials.

II.1.4 Discussion:

Substantial difficulties were encountered in sourcing seed of selected hemp cultivars and having done so, obtaining quality seed with good viability. Separate imported seed lots contained seed with poor germination percentages and evidence of insect damage. Low viability suggests deterioration through either prolonged storage and/or storage under high temperature or humidity (Toole *et al.* 1960). Suffice to say that future researchers should deal with reputable merchants and ensure that a certificate of quality is provided with imported seed. Furthermore, significant time delays were encountered due to the need for importation licences under both Tasmanian and Commonwealth legislation. Add to this the time for shipping, customs and quarantine clearance and there is a clear need to commence the process of importing seed at least six months prior to the intended sowing date.

In a study of cannabinoid levels in a large number of *Cannabis* genotypes, Meijer *et al.* (1992) reported considerable variation in THC levels. Whilst no strict relationships were found between chemical and non-chemical traits, wide leaflets and delayed flowering were found to be weakly associated with increased psychoactivity. Consistent trends of a similar nature were not apparent in the results of this current trial.

The seasonal instability in THC content observed in this study, has previously been

reported by Meijer *et al.* (1992). In a review by Pate (1994), cannabinoid levels are reported to be influenced by a wide array of environmental factors, including: temperature, humidity, wind, nutrient levels, ultraviolet radiation, competition and attack from insects, bacteria and fungi. Consequently, seasonal and site variation in cannabinoid levels are to be expected.

The positive relationship between days to flowering and stem production emphasises the importance of having cultivars that maintain vegetative growth for as much of the available growing season as possible. All the cultivars trialled in this study flowered before the end of January. Clearly, the relatively long, dry summer season in Tasmania could accommodate later flowering and potentially higher yielding cultivars. Meijer (1994) reported that Kompolti and Kompolti Hybrid TC have the slowest phenological development of the commercially available fibre cultivars. Later flowering landraces from Korea and Japan were found to give much higher stem yields than these cultivars, but had very poor bark percentages.

The three cultivars (Felina 34, USO 13 and USO 14) for which yield measurements could not be made, all flowered relatively early in the season. Consequently, further consideration of these cultivars for fibre production is not warranted.

Of the cultivars screened in these preliminary trials, Kompolti, Futura 77 and Unico B demonstrated the most promise in terms of their performance under Tasmanian conditions. Kompolti was subsequently selected for further crop management, physiology and processing studies.

II.2 The effect of sowing date on the growth and development of fibre hemp in Tasmania.

II.2.1 Introduction:

Published data relating sowing date and stem yield of hemp in Australia is limited. Valder (1893) reported on trials conducted at various locations in New South Wales in which an unnamed variety was sown at intervals from the end of August to early October. Severe frost damage occurred in early sowings at colder sites, leading to sowing date recommendation from October onwards. Earlier sowings were found to give higher stem yields at warmer, less frost prone localities.

In Europe, fibre hemp is usually sown between early March and late May depending on temperature and rainfall considerations (Reichart 1994) (Heuser 1927, Tschaneff 1959, Friederich 1964, Rivoira & Marras 1975 cited by van der Werf 1991).

Van der Werf *et al.* (1996) simulated the effect of sowing date in the Netherlands on the time of canopy closure and on the amount of accumulated photosynthetically active radiation (PAR). Sowing on April 15 instead of March 16, resulted in a 12 day delay in canopy closure and a reduction in intercepted PAR of 120 MJ/m^2. Similarly, sowing on May 15 instead of April 15, resulted in a 19 day delay in canopy closure and a reduction in intercepted PAR of 185 MJ/m^2. These results reflect the ability of hemp to grow well at low temperatures, having base temperatures of 1 ^oC for leaf appearance and emergence, and 2.5 ^oC for canopy establishment (van der Werf *et al.* 1995).

Notwithstanding the benefits from early sowing in terms of light interception, the limiting factor in many locations in Europe is the potential for frost damage. Hemp seedlings survive a short period of frost down to -8 to -10 ^oC (Grenikov & Tollochko 1953, cited by van der Werf *et al.* 1996); older hemp plants tolerate frosts of down to -5 to -6 ^oC (Senchenko & Timonin 1978, cited by van der Werf *et al.* 1996).

The objective of this study was to investigate the response of two hemp cultivars to a range of sowing dates in Tasmania. Interactions between sowing date and plant

density were also investigated.

II.2.2 Materials and method:

Design and treatments:

Separate sowing date by cultivar trials were established in the 1994-95 season at the University of Tasmania Farm, Cambridge (42°50'S, 147°30'E) (Trial 1) and at the Forthside Research Station (41°10'S, 146°40'E) (Trial 2). A third trial was conducted at Forthside during the 1996-97 season to assess the interaction of sowing date and plant density (Trial 3). Kompolti was used for this last trial.

Table II.2.1: Treatment combinations for the three trials at Cambridge and Forthside.

Trial 1:	Trial 2:	Trial 3:
Cambridge 1994-95.	**Forthside 1994-95.**	**Forthside 1996-97.**
2 Cultivars:	2 Cultivars:	3 Sowing dates:
Kompolti	Kompolti	3.10.96 (SD1)
Fedrina 74	Fedrina 74	23.10.96 (SD2)
4 Sowing dates:	4 Sowing dates:	6.11.96 (SD3)
30.5.94 (SD1)	21.9.94 (SD1)	3 Plant densities:
14.10.94 (SD2)	10.10.94 (SD2)	40 plants/m^2 (PD1)
2.11.94 (SD3)	24.10.94 (SD3)	90 plants/m^2 (PD2)
17.11.94 (SD4)	8.11.94 (SD4)	140 plants/m^2 (PD3)

The treatments are summarised in Table II.2.1. The trials were established as split plot designs with four replicates of each treatment combination. In trials 1 and 2, sowing dates occupied the first stratum and cultivars the second stratum. In trial 3, sowing date occupied the first stratum and plant density the second stratum. Plot size was 12 m^2 for trials 1 and 2, and approximately 8 m^2 for trial 3. A buffer zone of one plot width (cv. Kompolti) was sown around each trial to minimise edge effects.

Attempts to trial a fifth sowing date in early spring at Cambridge (trial 1) were not

successful due to a mechanical fault in the cone seeder drilling equipment at the time of sowing. Furthermore, delays in the arrival of seed of Fedrina 74 prevented an autumn sowing (SD1) of this cultivar in the Cambridge trial.

Cultural methods:

Seed was sown to a depth of 3-4 cm and with a row spacing of 15 cm using a 10 row cone seeder. Trials 1 and 2 were sown at a seeding rate of 80 kg/ha. Trial 3 was sown at a seeding rate to achieve a target plant density at emergence of ~200 plants/m^2. Plots were then hand thinned back to the required treatment density.

Fertiliser application was based on soil test results and target soil reserves of 100 kg/ha N, 40 kg/ha P and 100 kg/ha K. Composite fertiliser with an N:P:K ratio of 9:14:17 was predrilled in each trial; 300 kg/ha at Cambridge and 400 kg/ha in the two trials at Forthside. This was followed by a topdressing of nitrogen fertiliser at 40 kg N/ha shortly after emergence.

Irrigation and weed control measures were identical to those described in Chapter II.1.

Data collection & analysis:

Stem rot from infection with *Sclerotinia sclerotiorum* was apparent on isolated plants in both trials at Forthside. However, losses were not regarded as significant. Smaller losses from infection with *Alternaria sp.* were observed at Cambridge.

In trials 1 and 2, sequential harvests of 0.5 m^2 were collected at regular intervals, allowing 0.5 m of plot length as a buffer between each sample. The final harvest of 2 m^2 was collected at seed maturity. Diseased plants were not included in the harvests.

No sequential harvests were collected from trial 3. The trial plots were harvested at the late flowering stage, just prior to seed set.

Total above ground fresh weight and plant counts were measured for each sample. A random selection of 20 plants was then set aside for partition analysis and the

measurement of stem dimensions.

Measurements were made of leaf area index, stem length and stem diameter. Leaf area was measured using a Paton/CSIRO Electronic Planimeter. Stem length and diameter were measured in the same manner as described in Chapter II.1. Partitioned subsamples were then oven dried at 70 °C for 48 hours for dry matter and yield determination.

The proportion of bark in the stem was determined at maturity by manual separation using the method described in Chapter II.1.

Frequent observation of 20-30 tagged plants within each plot were used to monitor flowering and maturity times in the 1994-95 trials. Flowering was taken as the time when at least 50% of the tagged plants had one or more stigmatic female flowers or pedicillate male flowers visible to the naked eye. Seed maturity was taken as the time when 50% of the plants had mature seed or seed that was dark brown in color and resisted compression when pressed. In trial 3, samples of approximately 20 plant tops were collected at frequent intervals about the expected time of flowering. The time of flowering was based on dissections under a low power binocular microscope.

Trial 1 was sprayed with Lemat® at a rate of 50 ml/ha in July 1994 to control an infestation of red legged earth mite (*Halotydeus destructor*).

Analysis of variance tests were performed using Systat 5.2.1 software. Means were compared using the Fisher LSD test with significance for P values less than 0.05. In the absence of an autumn sowing of Fedrina 74 in trial 1, statistical comparisons were made between the spring sowings only. Data from the autumn sowing of Kompolti in trial 1 is shown separately (italics in Table II.2.2b), based on samples collected from four replicate plots.

II.2.3 Results:

Plant population:

Trials 1 & 2: Sowing date X cultivar trials, 1994-95:

The high seeding rate used for these trials resulted in self thinning, where many

Table II.2.2: Final harvest results for trials 1 and 2.
F and K denote Fedrina 74 and Kompolti respectively.
Fisher LSD figures shown with extent of significance, ie*P<0.05,**P>0.01,***P<0.001,n.s. not significant.

Trial 1: University Farm, Cambridge, 1994-95

	Density (plts/m^2)			Stem length (cm)			Stem diameter (mm)			Total D.M. (g/m^2)			Stem yield (g/m^2)			Bark percentage		
	K	F	Av.	K	F	Av.	K	F	Av.	K	F	Av.	K	F	Av.	K	F	Av.
SD1: 30.5.94	*260*			*51*			*4.6*			*383*			*234*			*39.8*		
SD2: 14.10.94	220	191	206	190	167	178	6.5	6.4	6.5	1454	1415	1435	1308	1108	1208	40.9	33	37
SD3: 2.11.94	180	135	158	202	183	193	7.1	7.5	7.3	1314	1266	1290	1164	985	1075	42.1	35.5	38.8
SD4:17.11.94	119	94	106	203	193	198	9.1	8.8	9	1245	1249	1247	1090	991	1041	41.7	35.7	38.7
Average	173	140		198	181		7.6	7.6		1338	1310		1188	1028		41.6	34.7	
Interaction	n.s.			n.s.			n.s.			n.s.			n.s.			n.s.		
Main S.D. effect	48**			11*			1**			122*			84.2**			n.s.		
Main cv. effect	12***			9**			n.s.			n.s.			108*			1***		

Trial 2: Forthside Research Station, 1994-95.

	Density (plts/m^2)			Stem Length (cm)			Stem diameter (mm)			Total D.M. (g/m^2)			Stem yield (g/m^2)			Bark percentage		
	K	F	Av.	K	F	Av.	K	F	Av.	K	F	Av.	K	F	Av.	K	F	Av.
SD1: 21.9.94	306	225	266	206	158	181	5.8	5.8	5.8	1455	1222	1338	1282	945	1114	41.7	34.2	37.9
SD2: 10.10.94	246	182	214	203	178	190	6.1	6.1	6.1	1443	1254	1348	1271	972	1122	40.2	33.3	36.8
SD3: 24.10.94	308	210	259	183	157	170	5.6	5.1	5.4	1229	1196	1212	1054	909	981	37.6	32.8	35.2
SD4: 8.11.94	254	215	235	182	165	173	5.7	4.8	5.2	1058	1166	1112	962	849	905	38.2	30.5	34.4
Average	279	208		193	164		5.8	5.5		1296	1209		1142	919		39.4	32.7	
Interaction	n.s.			***			*			*			n.s.			n.s.		
Main S.D. effect	n.s.			9**			0.6*			127**			43*			2.2*		
Main cv. effect	19***			3***			0.2**			82*			94***			1.3***		

Table II.2.3: Final harvest results for trial 3.
Fisher LSD figures shown with extent of significance, ie*P<0.05,**P>0.01,***P<0.001,n.s. not significant.

	Density (plants/m^2)			Stem length (cm)				Stem diameter (mm)			
	PD1	PD2	PD3	PD1	PD2	PD3	Av.	PD1	PD2	PD3	Av.
SD1: 3.10.96	45	69	114	296	278	275	283	18.4	14.7	13.4	15.5
SD2: 23.10.96	49	83	94	277	242	246	255	16.5	13.4	11.6	13.8
SD3: 6.11.96	44	75	100	250	249	245	248	14.4	12.6	11.1	12.7
Average	46	76	103	274	256	255		16.4	13.6	12.0	
Interaction				*				n.s.			
Main S.D. effect				27***				1.4***			
Main Den. effect				12**				1.0***			

	Total D.M. (g/m^2)				Stem yield (g/m^2)				Bark percentage			
	PD1	PD2	PD3	Av.	PD1	PD2	PD3	Av.	PD1	PD2	PD3	Av.
SD1: 3.10.96	1551	1674	1537	1587	1334	1434	1341	1370	45.7	45.5	44.8	45.3
SD2: 23.10.96	1617	1119	1199	1312	1348	934	1025	1102	45.4	43.2	44.0	44.2
SD3: 6.11.96	954	1067	930	984	794	903	790	829	44.0	44.7	43.4	44.0
Average	1296	1209	1222		1159	1090	1052		45.0	44.5	44.1	
Interaction	n.s.				* *				n.s.			
Main S.D. effect	252***				217***				n.s.			
Main Den. effect	n.s.				n.s.				n.s.			

plants were outcompeted by stronger neighbours and remained weak and small. The final harvest plant densities shown in Table II.2.2 include all standing plants, many of which were thin and short and did not make a substantial contribution to final stem yield. The significantly larger harvest densities for Kompolti at both sites, were attributed to the higher germination percentage of this cultivar (96%) relative to Fedrina 74 (76%). A significant decline in population with delayed sowing in spring was apparent at Cambridge. Damage from birds shortly after emergence was at least partly responsible for plant loss in the November 2 sowing. Stress related to strong, hot winds experienced in November may have been another contributing factor.

Trial 3: Sowing date X plant density trial, 1996-97:
Self thinning was apparent in PD2 and PD3, as shown by the reduction in final harvest plant density relative to the initial target density established shortly after emergence (Table II.2.3). The reduction was most pronounced for PD3. In contrast to the earlier trial, severely stunted plants were not included in final harvest plant counts.

Dry matter distribution:
Trial 2: Sowing date X cultivar trial, Forthside 1994-95:
Figure II.2.1 shows the distribution of above-ground dry matter with time for the eight treatment combinations of trial 2. Total and stem dry matter peaked shortly after the commencement of flowering. Subsequent declines in total dry matter were partly due to leaf senescence. Declines in stem dry matter after flowering indicate mobilisation of stored food reserves into reproductive structures.

Total dry matter, stem yield and bark percentage:
Trials 1 & 2: Sowing date X cultivar trials, 1994-95:
At Forthside, final harvest total dry matter was largest for the earliest two sowings of both cultivars. For Kompolti, the total dry matter of SD3 was greater than that of SD4. Kompolti produced significantly more dry matter than Fedrina 74 for the first two sowings. Stem yield was greatest for Kompolti and declined significantly across the final three sowing dates (Table II.2.2a).

The May 30 sowing of Kompolti at Cambridge suffered losses from waterlogging

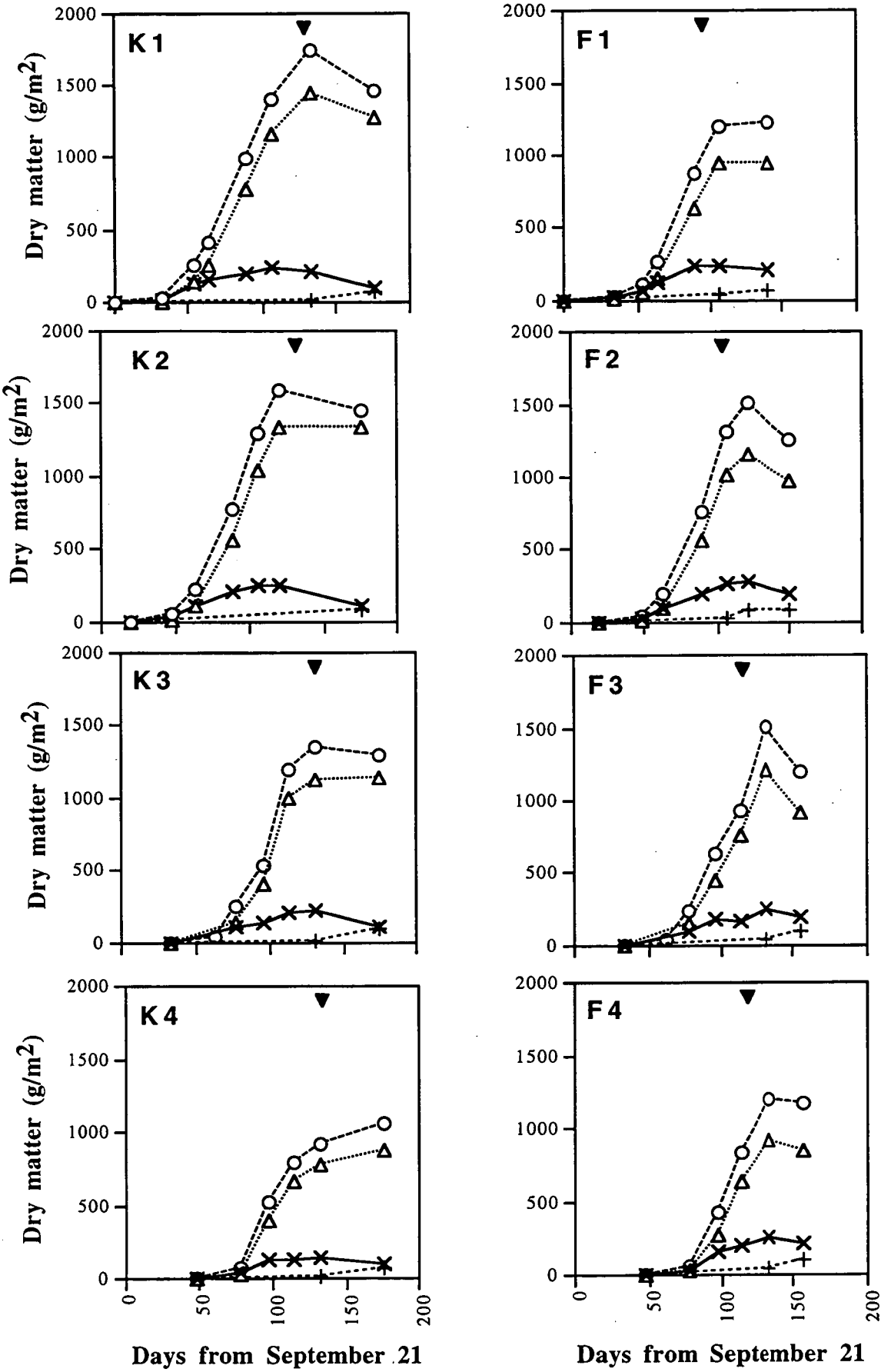


Figure II.2.1: The distribution in time of partitioned dry matter (total o, stem Δ, leaf x, inflorescence & seed +) for Fedrina (**F**) and Kompolti (**K**) for the four sowing date treatments (**1-4**) in trial 2 (sowing date X cultivar trial, Forthside, 1994-95). The arrows indicate the date of flowering.

during the winter months. This waterlogging was attributed to the presence of a shallow clay subsoil at the trial site. Non-fatal frost damage in the form of leaf tip burn was also observed during winter. Flowering occured in late August, resulting in very short plants and a poor stem yield (Tables II.2.2b and II.2.4).

Of the spring sowings at Cambridge, final harvest total dry matter and stem yield were greatest for SD2. Differences between the final two sowings were insignificant. Main cultivar effects were apparent for stem yield, with Kompolti yielding significantly more than Fedrina 74 (Table II.2.2b).

In both trials, Kompolti had a significantly higher bark percentage than Fedrina 74. At Forthside, SD1 gave a higher percentage than the final two sowings. Similarly, SD2 gave a higher percentage than SD4.

Trial 3: Sowing date X plant density trial, 1996-97:
Total dry matter declined with delay in sowing date across all densities (Table II.2.3). Similarly, stem yield declined with delay in sowing at 140 plants/m^2. At 90 plants/m^2, stem yield was maximum for SD1, whereas at 40 plants/m^2, stem yield was maximum for SD1 and SD2. Differences in total dry matter, stem yield and bark percentage with plant density were not significant. Average figures within each stratum did however indicate a declining trend in bark percentage with increasing plant density and delay in sowing date.

Stem dimensions:
Trials 1 & 2: Sowing date X cultivar trials, 1994-95:
Main sowing date effects were significant at the Cambridge site for both diameter and stem length (Table II.2.2b). Kompolti was generally taller than Fedrina 74. Treatments SD3 and SD4 had the tallest plants. The latest sowing produced plants with the largest stem diameter at final harvest. These responses for stem dimensions are opposite to those observed in the other two sowing date trials at Forthside and are most likely due to a density effect. In a separate density trial described in the following chapter, stem length and diameter generally decreased with increasing density. Similarly, van der Werf *et al.* (1995) observed that final harvest stem length decreased with increasing plant density.

At Forthside, a significant cultivar X sowing date interaction was apparent for both stem diameter and length (Table II.2.2a). Kompolti stems were taller than those of Fedrina 74 at all sowings and significantly thicker than Fedrina 74 for the final two sowings. The first two sowings of Kompolti were the tallest, whilst SD2 gave the tallest Fedrina 74 plants. Differences in stem diameter across the sowing dates of Kompolti were insignificant. The first two sowings of Fedrina 74 gave the thickest stems.

Trial 3: Sowing date X plant density trial, 1996-97:
There was evidence of an interaction between sowing date and plant density for stem length (Table II.2.3). The earliest sowing gave the thickest and tallest stems. In the case of the 40 plants/m^2 population, the difference between SD1 and SD2 was insignificant. Stem diameter generally decreased with increasing plant density. Stem length was maximum at 40 plants/m^2 for SD2 and SD3.

Flowering:
Trials 1 & 2: Sowing date X cultivar trials, 1994-95:
Kompolti flowered later than Fedrina 74 at both sites and across all sowing date treatments. Thermal time and calendar day duration from sowing to flowering tended to decline with delay in sowing date in spring (Table II.2.4). The extent of this decline was greater for Kompolti, with all spring sowings flowering within about one week of each other. Flowering of the spring sowings of Fedrina 74 were spread out over approximately a three week period. Despite higher seasonal temperatures at Cambridge, flowering tended to occur slightly later than at Forthside. This could be partly attributed to the delaying effect of greater daylengths at Cambridge.

Trial 3: Sowing date X plant density trial, 1996-97:
The trend in the dates and durations to flowering in this second trial were similar to those observed in the earlier trials. There was no apparent difference in flowering time with plant density treatment. The much earlier flowering dates recorded in this second trial at Forthside compared with the first trial in 1994-95, are attributed to differences in the method employed to determine flowering. In the early trials, the time of flowering was determined from infrequent (10-14 days) observations with the naked eye. In the 1996-97 trial, flowering was determined by dissection and

examination under a microscope at 4-5 day intervals about the expected time of flowering. The latter would be expected to give more accurate and earlier estimates of flowering time.

Table II.2.4: Date of flowering, calendar days and thermal time (above a base temperature of 1 °C) from sowing to flowering for Kompolti (K) and Fedrina 74 (F) in each trial.

Trial 1: Cambridge 1994-95:

	Date:		Calendar Days:		Thermal time:	
	K	F	K	F	K	F
SD1	24.8.94	-	86	-	668	-
SD2	2.2.95	7.1.95	111	84	1673	1233
SD3	5.2.95	22.1.95	95	80	1481	1259
SD4	7.2.95	28.1.95	82	71	1335	1176

Trial 2: Forthside 1994-95:

	Date:		Calendar Days:		Thermal time:	
	K	F	K	F	K	F
SD1	29.1.95	25.12.94	129	95	1586	1039
SD2	31.1.95	3.1.95	112	84	1485	1030
SD3	31.1.95	13.1.95	98	80	1347	1054
SD4	3.2.95	16.1.95	86	68	1214	938

Trial 3: Forthside 1996-97 (Kompolti):

	Date:	Calendar Days:	Thermal time:
SD1	11.1.97	101	1141
SD2	14.1.97	84	1014
SD3	20.1.97	76	970

II.2.4 Discussion:

The results from these sowing date trials suggest that September is the optimum month for sowing hemp in Tasmania. Later sowings resulted in a reduction in stem yield associated with a shortening of the thermal time duration from sowing to flowering. Furthermore, van der Werf *et al.* (1996) report yield declines from later sowings due to delays in canopy closure and a subsequent reduction in intercepted radiation. The response was most pronounced in sowings of Kompolti, which flowered within a short period of one another and differed more substantially in durations to flowering. In the 1996-97 trial at Forthside, the decline in stem yield between Kompolti sowings on October 3 and November 6 was as high as 41%. Furthermore, there was some evidence of a decline in bark percentage with delay in sowing date.

Sowings prior to September appear to be limited by premature flowering in response to short daylengths. The May 30 sowing of Kompolti at Cambridge, flowered in August. A non replicated, semi-commercial sowing at the same site on August 30 showed an apparent dual flowering response, with partial flowering in early November and the majority of flowering occurring in late January. The success of early sowings in Tasmania clearly depends on finding less photoperiod sensitive cultivars and cultivation on well drained sites. Whilst frost is a limitation in much of Europe (van der Werf *et al.* 1996), it is unlikely to limit sowing date selection in the main cropping areas of Tasmania.

The response of Kompolti and Futura 77 to a range of photoperiods was investigated in a separate controlled environment study described in Chapter IV.2.

Plant density appeared to have little influence on the response to sowing date in the 1996-97 trial at Forthside.

Similar findings to those reported here have been observed in concurrent trials conducted in other mainland Australian states. In preliminary trials with a range of French cultivars in South Australia, the optimum sowing time was found to be between October and November (Ditchfield *et al.* 1997). In field trials conducted at Myrtleford (~36°S) in Victoria, with a range of French varieties, plots sown on October 28 produced lower stem yields than those sown on November 21. This

was attributed to earlier flowering of the October sowing in response to exposure to shorter days (Lolicato *et al.* 1996).

II.3 Plant density effects on fibre hemp performance.

II.3.1 Introduction:

The primary objective of this trial was to investigate the influence of plant density on the productivity of an irrigated hemp crop grown in Tasmania. A secondary aim was to collect data relating to leaf area production and light interception for use in the development of a hemp simulation model (Section IV).

In a review by van der Werf (1991), recommended seeding rates for stem production were found to vary from 20 kg/ha to 100 kg/ha. These rates correspond to plant densities of approximately 100 and 500 plants/m^2 shortly after emergence. However, most reported seeding rates fall within the range suggested by Kirby (1963) of 40-60 kg/ha (~200-300 plants/m^2).

In a recent study incorporating plant populations of 10, 30, 90 and 270 plants/m^2, the stem yield response of hemp was found to be parabolic in shape (van der Werf *et al.* 1995a). At the 90 and 270 plants/m^2 treatments, a proportion of the population died as a result of self thinning, attributed to strong inter-plant competition effects.

Van der Werf *et al.* (1995a) used methods developed for forestry and ecology to describe self thinning in hemp. Self thinning implies that an increase in biomass is accompanied by a reduction in the number of living plants. The time course of self thinning on a plot of log biomass versus log plant density is called a self thinning trajectory. This trajectory approaches and follows a straight line referred to as the self thinning line, described by an equation of the form:

$\log Y = \log k - b \log \rho$,

where k and b are constants, Y is the total dry matter (g/m^2) and ρ is the density (plants/m^2). The self thinning line for hemp was observed to have a shallow slope relative to other herbaceous dicots (Weller 1987), a response attributed to a smaller rate of increase in biomass packing (dry matter per unit volume).

Quality issues also influence decisions regarding optimum density. Jakobey (1965) found that bark fibre content and fibre fineness increased with density. This

suggested that the optimum density based on fibre quality considerations may lie beyond that for yield. Van der Werf *et al.* (1995a) observed significant increases in bark content with density up to 90 plants/m^2. Subsequent decreases in crop growth rate and bark content beyond this density were attributed to the detrimental effects of self thinning. It was concluded that the optimum plant density is that which maximises the beneficial effects of high plant density in terms of using resources most efficiently, while minimising the negative effects linked with self thinning.

The yield/density response:

The response between yield and plant density is usually either asymptotic or parabolic, depending on whether yield approaches an asymptote with increasing density or whether it subsequently declines at higher densities (Willey & Heath 1969). The yield response function is a consequence of inter-plant competition effects. In the early stages of growth when competition is negligible, yield will usually increase linearly with density. As time progresses, the response function will tend to plateau above a certain density, signifying the reduced growth rate of plants competing for limited resources (Harper 1983).

Both Ratkowsky (1983) and Willey & Heath (1969) discuss a variety of mathematical functions which have been proposed to describe the yield/density relationship. Models based on a mathematical relationship between the reciprocal of mean yield per plant and density are generally preferred because: (a) they have a biological foundation; (b) they describe the yield/density relationship over a wide range of densities; and (c) they facilitate construction of yield/density curves from a minimum of data (Willey & Heath 1969). The simplest model, first developed by Shinozaki and Kira (1979), involves a direct linear relationship between the reciprocal of yield per plant and density:

$$w^{-1} = a + b.\rho,$$

where a and b are constants, w is the yield per plant and ρ is the plant density. Although this model is satisfactory for asymptotic yield density relationships, it is not appropriate for describing parabolic responses. Ratkowsky (1983) proposed that the relationship developed by Holliday (1960) is the most suitable for the parabolic yield/density situation. This is a quadratic expression:

$$w^{-1} = a + b.\rho + c.\rho^2,$$

where a, b and c are constants.

II.3.2 Materials and method:

Design & treatments:

A randomised complete block design was employed with four replicates. Each plot was 1.6 m wide by 10 m long. A buffer zone of one plot width (cv. Kompolti) was sown on either side of the trial area to minimise edge effect.

Treatments included five plant densities 50, 80, 120, 200 and 300 plants/m^2.

Cultural methods:

The trial was sown on September 26, 1996 at the Forthside Research Station (41°10'S, 146°40'E).

The cultivar Kompolti was sown to a depth of approximately 3-4 cm using a 10 row cone seeder with 13.5 cm row spacings and 1.6 m plot centres. The entire trial area was sown at a seeding rate of 80 kg/ha. Final target densities were established by hand thinning approximately 5-7 days after emergence.

Fertiliser rates were based on a soil test and literature recommendations for hemp production (100-130 kg N/ha, 35-50 kg P/ha and 110-140 kg K/ha). A blend of 9:14:17 NPK fertiliser (350 kg/ha) and zinc sulphite monohydrate (30 kg/ha) was incorporated into the top 15-20 cm of the soil profile just prior to drilling. A further topdressing of nitrogen (40 kg/ha) fertiliser was applied 4-6 weeks after sowing.

Irrigation and weed control methods were the same as those described in Chapter II.1.

Stem rot (*Sclerotinia sclerotiorum*) was apparent on isolated plants around flowering but losses were not regarded as significant.

Data collection & analysis:

To monitor changes in plant population, small areas of 1m^2 were pegged out within each plot and counts made on a regular basis.

The dates of flowering were determined in the same manner as described in Chapter II.1.

Sequential harvests of 0.5 m^2 were collected at regular intervals, allowing 0.5 m of plot length as a buffer between each sample (Table II.3.1). The final harvest of 2 m^2 was collected at late flowering. Senesced leaf matter and severely suppressed (a result of 'self thinning') living plants were not included in density counts or sequential harvests.

Table II.3.1: Dates and days from sowing of sequential and final harvests.

Harvest	Date	Days from sowing
H1	4.11.95	39
H2	21.11.95	56
H3	5.12.95	70
H4	20.12.95	85
H5	8.1.96	104
H6	30.1.96	126

Total above-ground fresh weight and plant density were measured from each sample. A random selection of 20 plants was then taken for measurement of total green and senesced node number, leaf area index, stem length and stem diameter. Stem dimensions and leaf area index were determined in the same manner as described in Chapters II.1 and II.2. In hemp, phyllotaxis changes from opposite to alternate at or about the commencement of flowering. However, nodes still appear along the stem in distinct pairs. For the purposes of the study, paired nodes with alternate leaves were regarded as one node.

The subsample plants were then partitioned and oven dried at 70 ^oC for 48 hours to determine total dry matter and stem yield results. The proportion of bark in the stem was determined using the same method as described in Chapter II.1.

Regression analysis was conducted using Systat 5.2.1 software. Asymptotic and parabolic yield density relationships were determined by fitting Shinozaki and Kira (1956) and Holliday (1960) equations to plots of the reciprocal of yield per plant

versus initial density. Model selection was based on minimising the residual mean square. Analysis of variance tests were performed on total dry matter, yield, yield component and stem dimension results from the final harvest. Means were compared using the Fisher LSD test with significance for P values less than 0.05.

II.3.3 Results:

Plant population:

The number of surviving plants decreased with time for each density treatment (Figure II.3.1). Furthermore, the proportion of the plant population at emergence that survived to maturity decreased with increasing plant density. In the 300 plant/m^2 treatment, the rate of decline was relatively constant from shortly after emergence to approximately 100 days after sowing. Thereafter, the rate decreased dramatically. Whilst there was some evidence of plant death from infection with *Sclerotinia sclerotiorum*, these losses were minor and confined to late in the season.

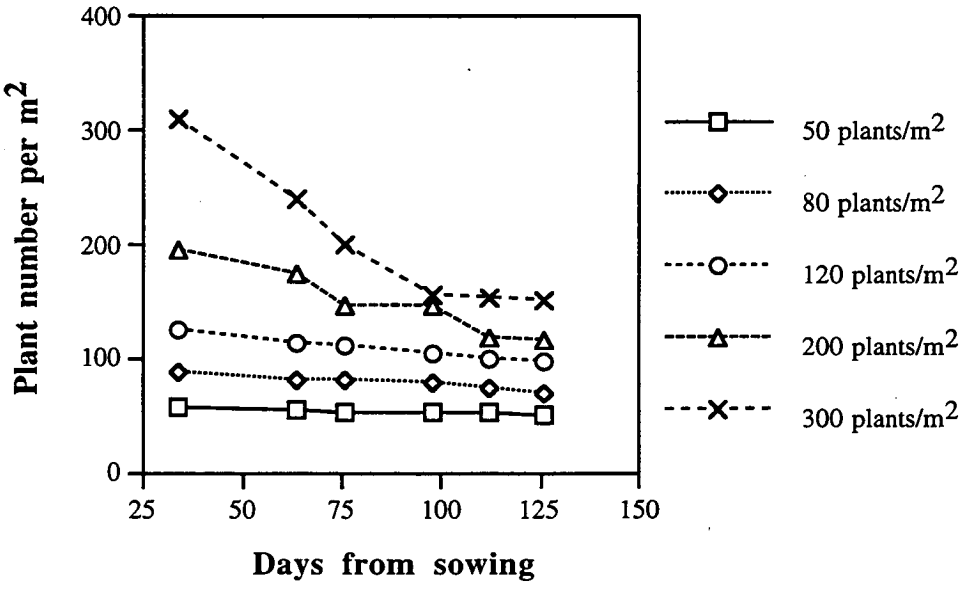


Figure II.3.1: Plant density (plants/m^2) versus days after sowing. Each point represents an average of three replicate counts.

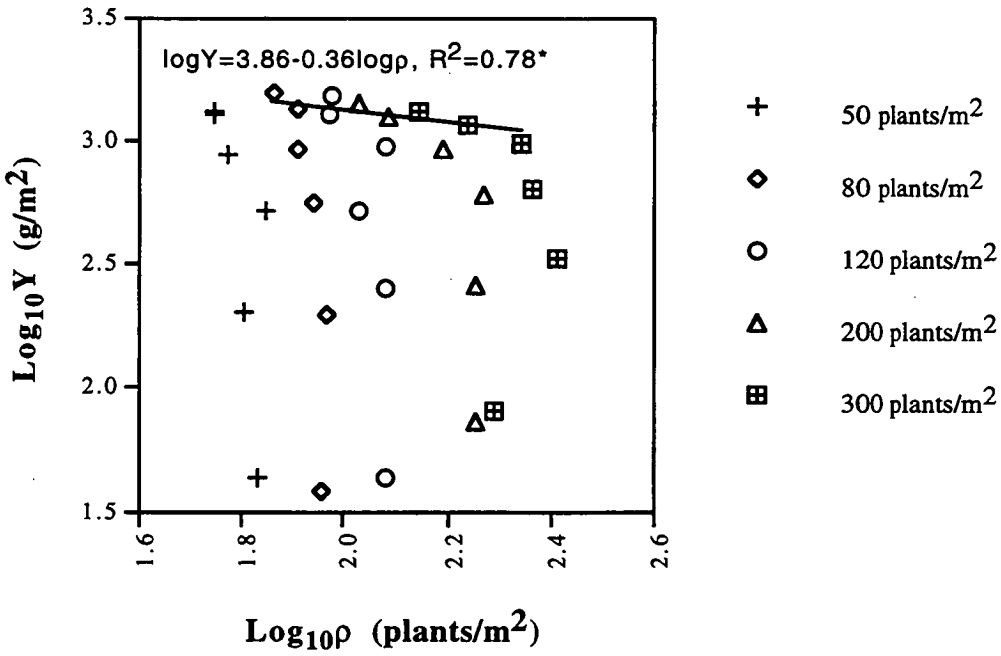


Figure II.3.2: $Log_{10}Y$ (total dry matter) versus $Log_{10}\rho$ (plant density) over time from H1 to H6. The thinning line was fitted to the points corresponding to H4 and H5 for treatments 80, 120 and 200 plants/m^2, and H4, H5 and H6 for the 300 plants/m^2 treatment.

This self induced mortality is attributed to inter-plant competition for available resources, a process which becomes more severe with higher initial plant densities. Plots of log total dry matter versus log plant density for the four highest density treatments approached and then followed the straight line;

$\log Y = 3.86 - 0.36 \log \rho$, $R^2=0.78^*$ (Equation 1).

This self thinning line relates the decline in population to increasing biomass. The plot for the 50 plants/m^2 treatment did not appear to reach the upper limit of total biomass defined by this line.

Yield and yield components:

Biomass production was slow up until about 8-9 weeks after sowing. Thereafter, total dry matter and stem yield increased rapidly up to flowering (Figure II.3.3). The rate of this increase subsequently declined between flowering and final harvest.

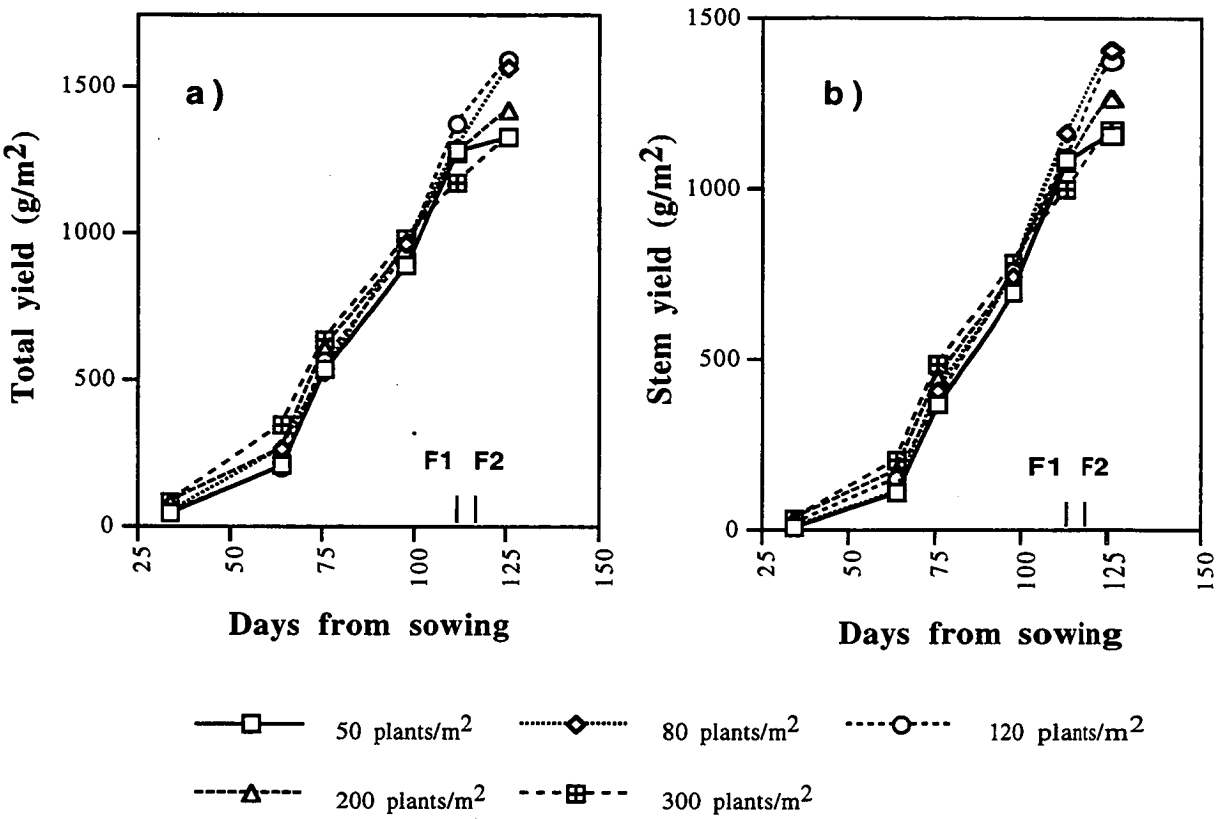


Figure II.3.3: Time response plots for total dry matter (a) and stem yield (b). The dates of flowering for 50, 80 and 120 plants/m² (112 DAS) and, 200 and 300 plants/m² (118 DAS) are denoted by F1 and F2 respectively.

Differences between flowering times for the treatments were difficult to identify. It was clear however, that plants at 200 and 300 plants/m² flowered later than in the other treatments. The difference was approximately 6 days.

The response of total dry matter per unit area (TDM) to density varied throughout the season (Table II.3.2). For H1, TDM increased linearly with density. For H2, H3 and H4, Shinozaki and Kira reciprocal equations gave the best fit to reciprocal plots, suggestive of an asymptotic response to initial density. For the final two harvests, Holliday equations provided the lowest residual mean square value, indicating a shift to a parabolic response. The maximum stem yield derived from the above equation for H6, corresponds to an initial plant density of 105 plants/m².

The responses of stem yield to plant density were similar to those for total dry matter (Table II.3.2).

Table II.3.2: Fitted linear equations for total dry matter and stem yield versus initial density (ρ) for harvests H1 to H6. W is yield per plant (g/plant) and Y is yield per unit area (g/m^2). The significance of the linear models is identified by the asterisks (P<0.05 *, P<0.01**, P<0.001***).

	Initial plant density (plants/m^2):						
Total dry matter (g/m^2):	50	80	120	200	300	Equation	R^2
H6	1326	1589	1560	1419	1330	$W^{-1}=8.7X10^{-3}+4.9X10^{-4}\rho+7.8X10^{-7}\rho^2$	0.99
H5	1285	1374	1290	1274	1174	$W^{-1}=5.6X10^{-3}+6.3X10^{-4}\rho+6.9X10^{-7}\rho^2$	0.99
H4	886	928	959	941	978	$W^{-1}=5.9X10^{-3}+1.0X10^{-3}\rho$	0.99***
H3	532	562	520	608	637	$W^{-1}=3.0X10^{-2}+1.5X10^{-3}\rho$	0.98***
H2	205	197	256	264	339	$W^{-1}=1.7X10^{-1}+1.5X10^{-3}\rho$	0.98**
H1	43	38	43	74	80	$Y=28+0.18\rho$	0.87*
	Initial plant density (plants/m^2):						
Stem yield (g/m^2):	50	80	120	200	300	Equation	R^2
H6	1155	1401	1372	1261	1167	$W^{-1}=1.2X10^{-2}+5.2X10^{-4}\rho+9.9X10^{-7}\rho^2$	0.99
H5	1081	1162	1089	1073	999	$W^{-1}=5.4X10^{-3}+7.7X10^{-4}\rho+7.2X10^{-7}\rho^2$	0.99
H4	693	737	760	749	778	$W^{-1}=8.4X10^{-3}+1.3X10^{-3}\rho$	0.99***
H3	365	401	375	444	486	$W^{-1}=5.9X10^{-2}+1.9X10^{-3}\rho$	0.98***
H2	106	109	145	170	203	$W^{-1}=3.6X10^{-1}+3.9X10^{-3}\rho$	0.97**
H1	10	9	12	26	28	$Y=4.1+8.6X10^{-2}\rho$	0.89*

Final harvest total dry matter and stem yield at 80 plants/m^2 were significantly larger than at 50, 200 and 300 plants/m^2 (Table II.3.3). Similarly, production at 120 plants/m^2 was superior to that at 50 and 300 plants/m^2.

Differences in the percentage of bark at final harvest were generally small and not significant. However, regression analysis of the response of bark percentage suggested a linear decline with increasing initial density ($Y=42-7.9X10^{-3}\rho$, $R^2=0.85$*). Bark yield per unit area followed a parabolic response described by the Holliday equation, $W^{-1}=3.7X10^{-2}+1.1X10^{-3}\rho+3.2X10^{-6}\rho^2$.

Table II.3.3: Analysis of variance results for the final harvest (H6) for yield, yield components and stem dimensions. Fisher LSD figures shown with extent of significance, ie *P<0.05, **P<0.01, ***P<0.001, n.s. not significant.

Plant density (plants/m^2)	50	80	120	200	300	LSD 0.05
Total D.M. (g/m^2)	1326	1589	1560	1419	1330	160**
Stem Yld. (g/m^2)	1155	1401	1372	1261	1167	138**
Bark percentage	41.7	41.1	41.0	41.0	39.3	n.s.
Node number	17.5	17.5	16	16.3	15.3	1.1**
Height (cm)	268	273	257	264	244	17**
Diameter (mm)	13.8	13.1	12	10.6	9.3	1.5***

Stem dimensions:

Stem diameter declined linearly with the logarithm of initial density, with significant R^2 values for harvests H2 to H6 (Figure II.3.4).

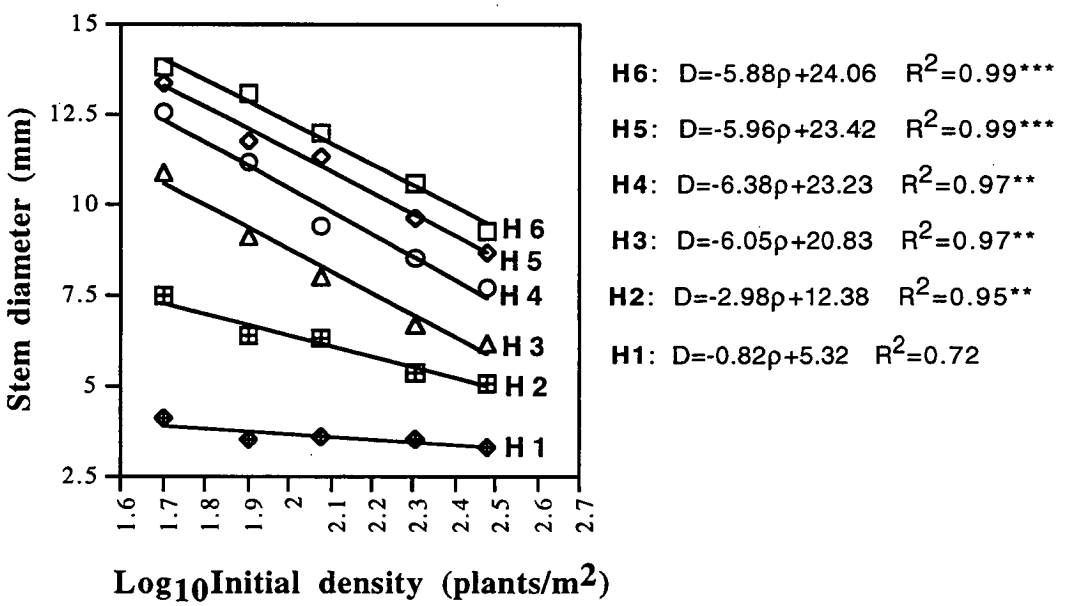


Figure II.3.4: Plot of average stem diameter (D, mm) versus the logarithm of initial plant density (ρ, plants/m^2) for each sequential harvest. Linear regression equations are shown for each response. The significance of the linear models is identified by the asterisks (P<0.05 *, P<0.01**, P<0.001***).

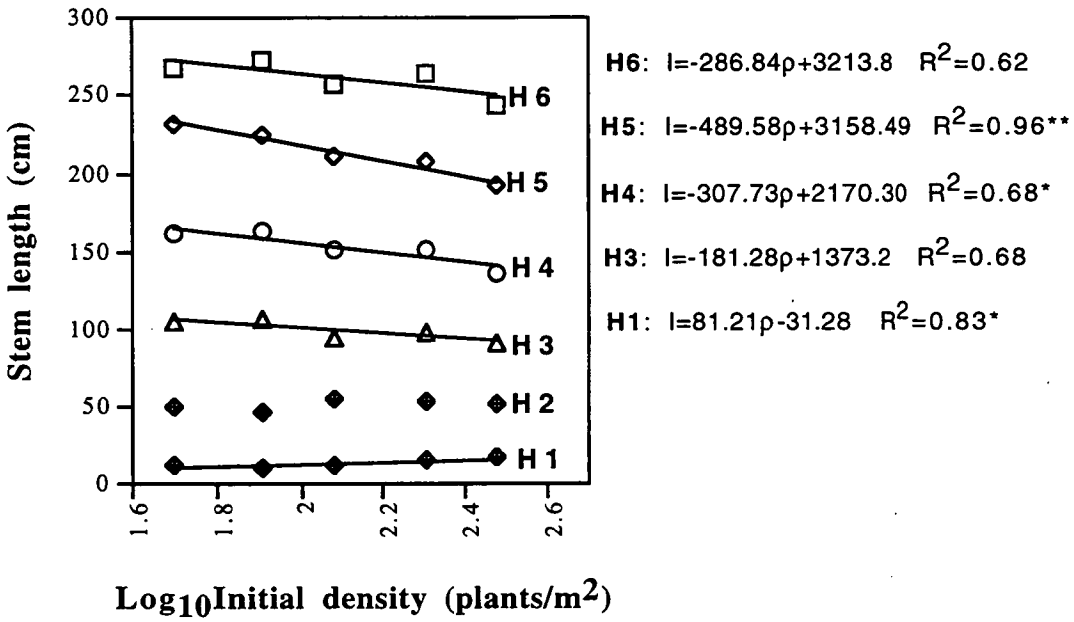


Figure II.3.5: Plot of average stem length (l, cm) versus logarithm of initial plant density (ρ, plants/m^2) for each sequential harvest. Regression equations are shown for each harvest response. The significance of the linear models is identified by the asterisks (P<0.05 *, P<0.01**, P<0.001***).

Stem length increased linearly with the logarithm of initial density for H1 and declined linearly for H4 and H5. Significant linear models could not be fitted to the results from H2, H3 and H6 although the general trend was similar to that for H4 and H5 (Figure II.3.5). The fitting of a quadratic model to the response at H6 did not improve the residual mean square value.

Leaf area production:

Leaf area production can be broken down into the component processes of leaf appearance, leaf expansion and leaf senescence. The response of these three processes to density is discussed in detail in Chapter IV.3.

Node number per plant declined linearly with the logarithm of initial density for each harvest (Figure II.3.6).

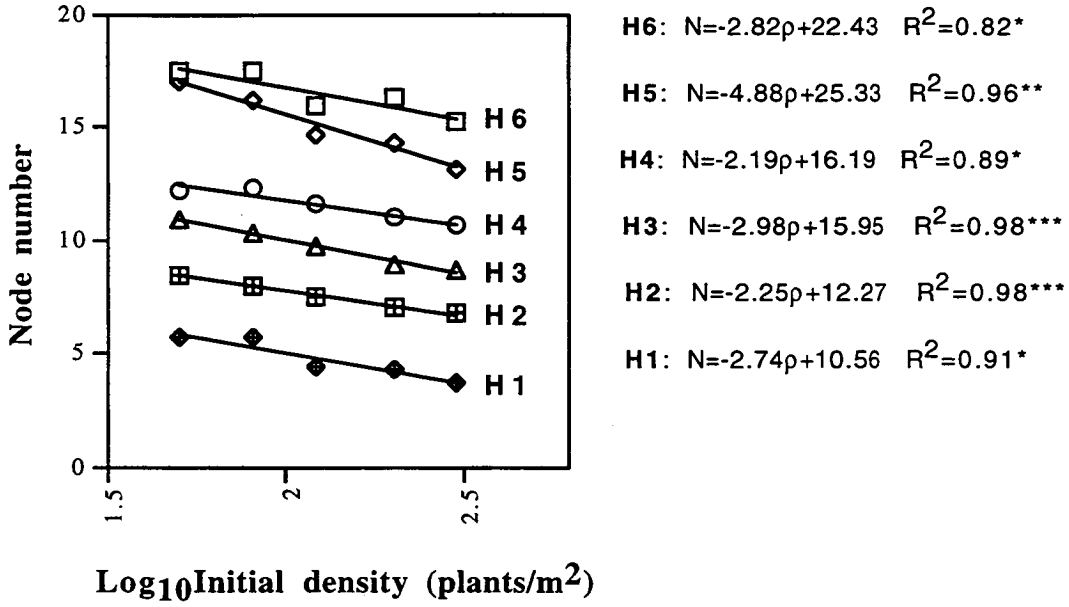


Figure II.3.6: Plot of node number per plant (N) versus the logarithm of initial plant density (ρ, plants/m²) for each sequential harvest. Linear regression equations are shown for each response. The significance of the linear models is identified by the asterisks (P<0.05 *, P<0.01**, P<0.001***).

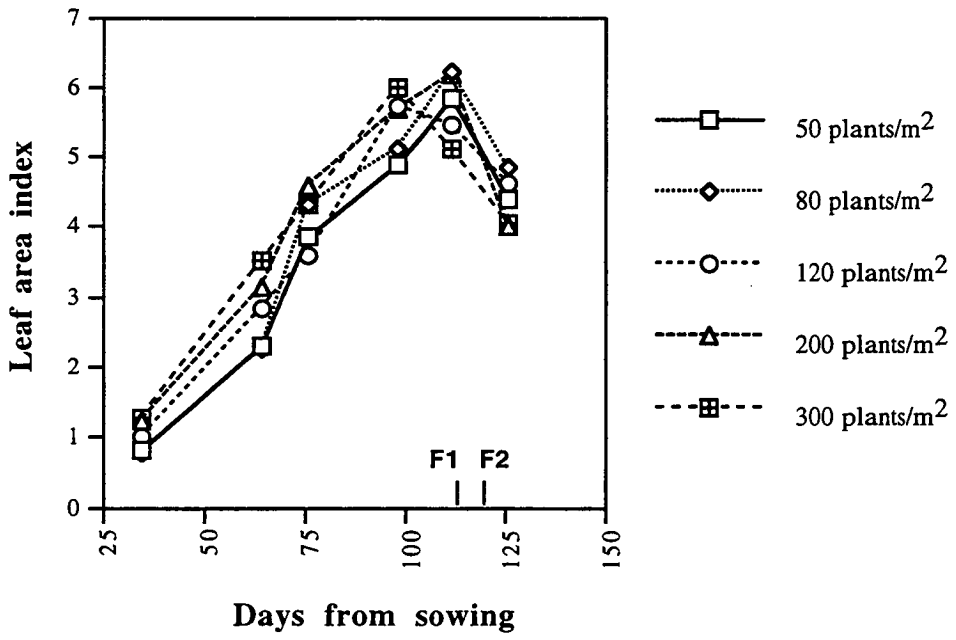


Figure II.3.7: Time response plots for leaf area index. The times of flowering for 50, 80 and 120 plants/m² (112 DAS) and, 200 and 300 plants/m² (118 DAS) are denoted by F1 and F2 respectively.

Green leaf area index (LAI) increased over time to a peak value of approximately 6 (Figure II.3.7). The smaller density treatments of 50 and 80 plants/m^2 reached the peak value after the 120 and 300 plants/m^2 treatments. This suggests a tendency for leaf expansion to be prolonged and senescence delayed in low density plantings. LAI increased linearly with initial plant density for H1, H2 and H4 (Figure II.3.8). Neither linear nor non-linear models adequately fitted the responses at the remaining harvests.

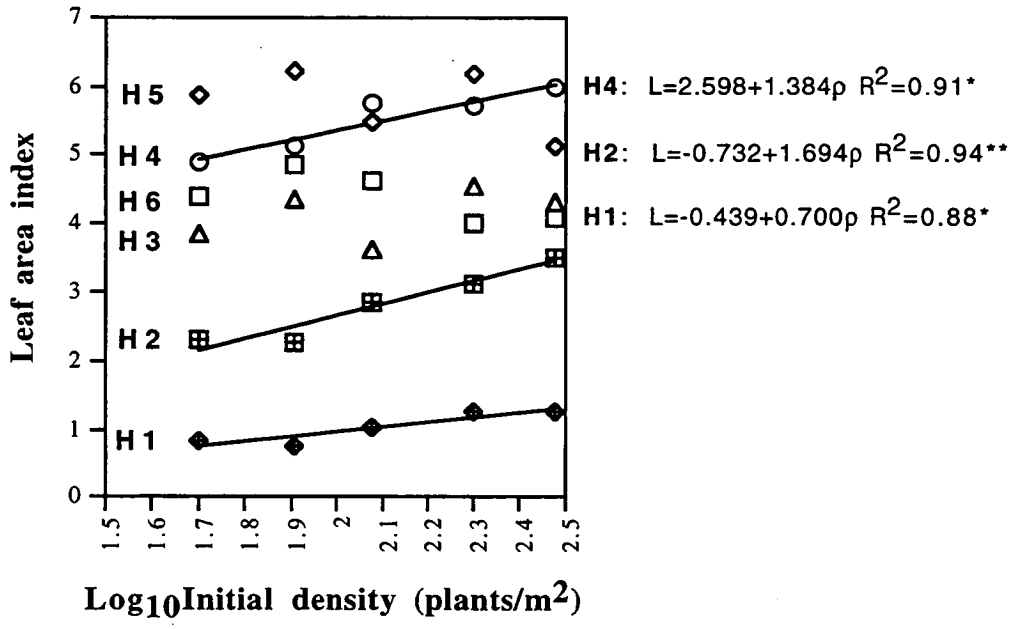


Figure II.3.8: Plot of leaf area index (L) versus the logarithm of intial plant density (ρ, plants/m^2) for each sequential harvest. Fitted linear equations are shown for selected harvests. The significance of the linear models is identified by the asterisks (P<0.05 *, P<0.01**, P<0.001***).

II.3.4 Discussion:

Plant number declined with time across all treatments and was most pronounced in the 200 and 300 plant/m^2 populations. The self thinning line which relates this decline to biomass production is similar to that previously reported by van der Werf *et al.* (1995a). For three Hungarian cultivars (including Kompolti), van der Werf *et al.* (1995a) determined a self thinning line of LogY=3.81-0.304Logρ. It was concluded that the maximum plant density that does not lead to self thinning is a function of expected yield. Therefore, based on the self thinning line determined in this current study (see Equation 1), maximum densities (to avoid self thinning) at

total dry matter yields of 1200, 1400 and 1600g/m^2 will be 148, 96 and 66 plants/m^2 respectively.

The early decline in plant number coupled with the response of various other crop parameters, indicate that competition effects occurred early in the season. The significant linear increases in stem height and stem proportion of total dry matter (results not shown) at H1, suggest increased assimilate allocation to the stem as a consequence of competition at higher densities. This is further reflected in the significant linear decline in node number and hence leaf appearance with increasing density. Despite these effects, total dry matter and stem yield per unit area increased linearly with initial density in the early harvests, presumably because of earlier canopy closure and hence greater light interception at higher densities (van der Werf *et al.* 1995a). This is supported by the linear increase in leaf area index with increasing density.

As competiton effects increased with time, the growth rates of plants at the lower densities would have increased relative to the suppressed plants at higher densities (Harper 1983). This is reflected in the increase in the slope of the linear diameter response from H1 to H4 and the increasingly negative slope of the height response after H1. Furthermore, the linear yield response became asymptotic and then, toward the final harvest, changed to a parabolic response.

Van der Werf *et al.* (1995a) reported an increase in bark percentage up to 90 plants/m^2 and a subsequent decline at higher self thinning populations. In this study however, there was a small but significant linear decline in bark percentage across the entire range of plant density treatments.

The significant response to plant density in this trial contrasts with the findings from the sowing date by plant density trial reported in Chapter II.3 in which there were no significant density effects on stem yield or bark percentage for treatments of 40, 90 and 140 plants/m^2. Nevertheless, parabolic trends were apparent for two of the sowings with maximum stem yields at 90 plants/m^2.

The Holliday equations fitted to the final harvest yield responses predict maximum stem and bark yields of 1351 and 561 g/m^2 respectively, at an establishment

density of approximately 110 plants/m^2.

II.4 Response of fibre hemp to varying irrigation regimes.

II.4.1 Introduction:

Preliminary field trials with hemp indicated that irrigation would be essential in order to overcome deficiencies in both the distribution and total amount of rainfall over the summer months in Tasmania. During the 1994/95 season, areas of a hemp trial which received insufficient water were severely stunted and gave poor stem and fibre yields in comparison to well watered sites. Furthermore, a growth model developed by Hackett (1991) identified rainfall shortages as a major limitation to hemp growth in three separate locations across southern Australia.

Hemp is said to be sensitive to drought and needs ample water, especially during the first 6 weeks of its growth (Dempsey 1976). At the same time, hemp is particularly sensitive to waterlogging. Thus, an ideal soil will have both good drainage properties and good water holding capacity.

Literature recommendations for the water requirements of fibre hemp are sparse and somewhat ambiguous. In the Ukraine, optimum yields are achieved with 250-280 mm of rainfall during the growing season (P. Goloborodko. pers. comm. 1994). Begg and Buller (1995) suggest a total available water requirement of approximately 600 mm. Van Dam (1995) reports that hemp requires rainfall of at least 650 mm per year.

The purpose of this trial was to examine the effect of a range of allowable soil water deficits on the yield and growth responses of hemp (cv. Kompolti). Sequential harvest data enabled examination of the ability of fibre hemp to recover from periods of water stress. Regular measurements of soil water content using a neutron moisture meter were used to develop soil water extraction profiles and to calculate seasonal water consumption and water use efficiency.

II.4.2 Materials and method:

Design & treatments:

A randomised complete block design was employed with four replicates. Each plot was 1.6 m wide and 10 m long. A buffer zone (cv. Kompolti) of one plot width was

sown around the perimeter of the trial area.

The five irrigation treatments covered a range of soil moisture deficits including 30 mm (I30), 60 mm (I60), 90 mm (I90), 120 mm (I120) and a rainfed treatment (I0). The number and dates of irrigations are shown in Table II.4.1. Deficits were based on cumulative, rainfall adjusted Class A pan evaporation measurements made within 500 m of the trial site. Upon reaching the treatment deficit, each of the four replicate plots was returned to field capacity.

Total rainfall for the duration of the trial was approximately 60mm above the average (38 year) rainfall total for the same period (Figure II.4.1). The distribution of rainfall was less favourable, with lower than average rainfall totals for the months of November and especially December. Over twice the average rainfall was received in January.

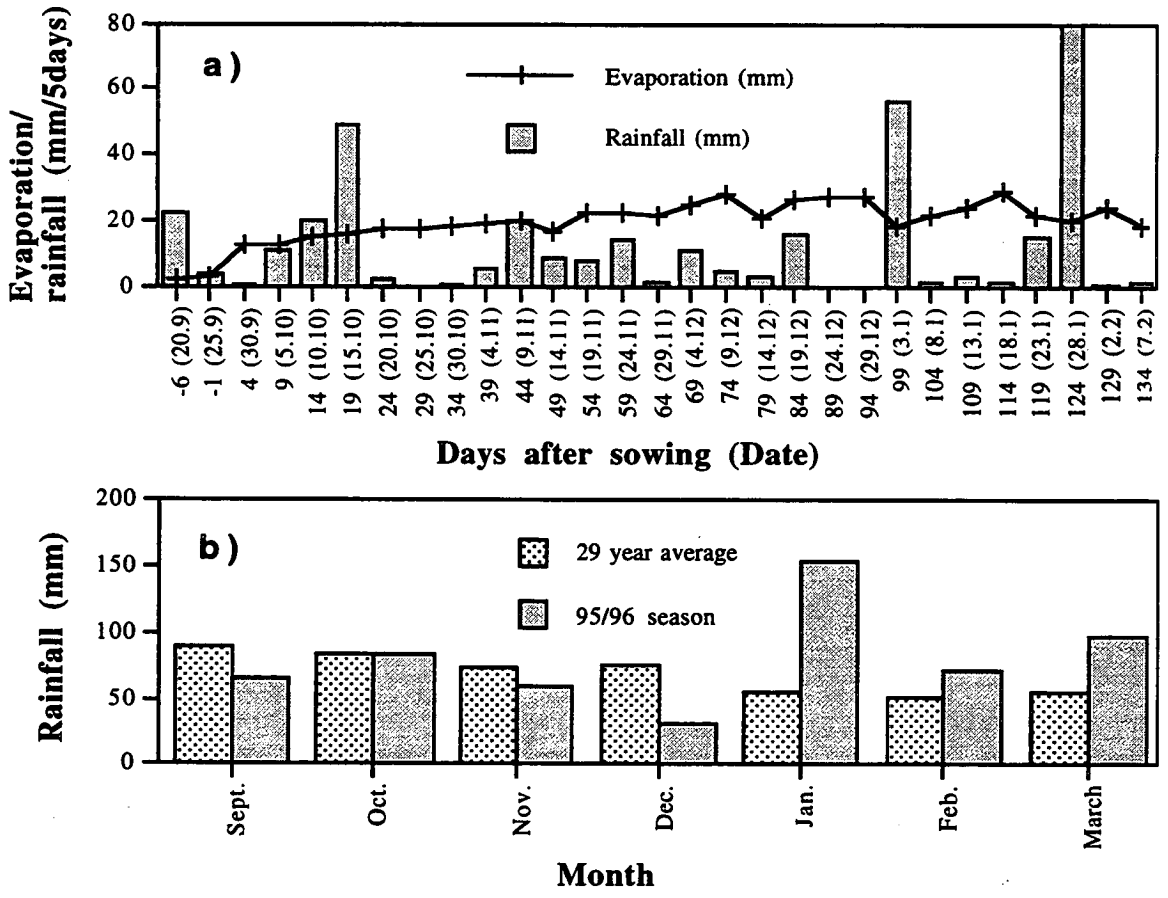


Figure II.4.1: (a) Total rainfall and Class A pan evaporation for five day periods (days after sowing and date (bracketted) along the X axis) from 20/9/95 to 7/2/96. (b) Monthly average rainfall totals from 1958-1996 and 1996-97 season monthly totals.

Table II.4.1: The number and dates of irrigation events for each treatment.

Treatment:	Number:	Dates (1995-96):
30mm (I30)	8	27.10/ 21.11/ 4.12/ 11.12/ 14.12/ 24.12/ 10.1/ 17.1
60mm (I60)	4	21.11/ 4.12/ 24.12/ 17.1
90mm (I90)	2	4.12/ 24.12
120mm (I120)	2	11.12/ 17.1
Rainfed (I0)	0	-

Cultural methods:

Seed of the cultivar Kompolti was sown to a depth of approximately 3-4 cm, using a 10 row cone seeder with 13.5 cm row spacings and 1.6 m plot centres. The entire trial area was sown at a seeding rate of 80 kg/ha, to establish a plant density of 150 plants/m^2.

The trial was sown on September 26, 1995 at the Forthside Research Station (41°10'S, 146°40'E) on a krasnozem soil. This soil is classified as a reddish brown, strongly structured, gradational, clay loam to clay soil. The amount of useful water held in these soils types at field capacity down to a depth of 70 cm, is typically moderate at 10-15% (Bridge & Bell 1994, Chilvers 1996). Leeper & Uren (1993) report that these soils are susceptible to drought but their structure is such that roots are able to penetrate deep into the profile to reach greater reserves of water.

Irrigation was applied with 'Netafim' flexible polyethylene drip tubing operated at a water pressure of 100 kPa and a delivery rate of 1.75 litres per hour per drip point. Four lengths of the flexible tubing were positioned along each plot at 30 cm spacings. Each set of treatment replicates were fed by a 19 mm polyethylene pipe which, in turn, was connected to a common 25 mm polyethylene pipe via an isolating tap.

Fertiliser rates were based on a soil test and literature recommendations for hemp production (100-130 kg N/ha, 35-50 kg P/ha and 110-140 kg K/ha). A blend of 9:14:17 NPK fertiliser (350 kg/ha) and zinc sulphite monohydrate (30 kg/ha) was

incorporated into the top 15-20 cm of the soil profile just prior to drilling. A further topdressing of nitrogen (40 kg/ha) fertiliser was applied 4-6 weeks after sowing.

The trial area was hand weeded at ten weeks. Thereafter, weed growth was adequately suppressed by the hemp crop.

Stem rot (*Sclerotinia sclerotiorum*) was apparent on isolated plants about the time of flowering but losses were not regarded as significant.

Data collection & analysis:

Sequential harvests of 0.5 m^2 were collected at two weekly intervals, allowing 0.5 m of plot length as a buffer between each sample. The final harvest of 2 m^2 was collected at late flowering (Table II.4.2). Dead and senesced leaf matter along with severely suppressed living plants (a result of 'self thinning') were not included in harvested samples.

Table II.4.2: Dates and days from sowing of sequential and final harvests.

Harvest:	Date:	Days from sowing:
H1	5.11.95	40
H2	21.11.95	56
H3	11.12.95	76
H4	2.1.96	98
H5	16.1.96	112
H6	5.2.96	132

Total above ground fresh weight and plant counts were measured for each sample. A random selection of 20 plants was then set aside for partition analysis.

Measurements were made of total node number, leaf area index, stem length and stem diameter using the same methods as described in Chapters II.1, II.2 and II.3. . Partitioned subsamples were then oven dried at 70 ^oC for 48 hours to determine total dry matter and stem yield results.

At final harvest, the proportion of bark in the stem was determined by manual

separation, as described in Chapter II.1.

A neutron moisture meter (N.M.M.) was used to measure changes in percent volumetric soil moisture content with depth. One aluminium recording tube was buried to a depth of 1.5 m in three replicate plots of each treatment. Moisture readings were made every 3-4 days and averaged across the three replicates. The data were subsequently processed using a software package entitled 'The Probe', developed by Neutron Probe Services Pty Ltd.

Analysis of variance tests were performed using Systat 5.2.1 software. Means were compared using the Fisher LSD test with significance for P values less than 0.05.

II.4.3 Results:

Final harvest results are listed in Table II.4.3.

Table II.4.3: Analysis of variance results for the final harvest. Fisher LSD figures shown with extent of significance, ie *P<0.05, **P<0.01, ***P<0.001, n.s. not significant.

Treatment:	I30	I60	I90	I120	I0	LSD 0.05
Plant density (plants/m^2)	120	114	107	127	125	n.s.
Total D.M. (g/m^2)	1552	1562	1454	1484	1217	166***
Stem Yld. (g/m^2)	1386	1379	1273	1315	1056	128***
Bark percentage	42.7	41.6	40.3	38.9	39.1	2.3*
Bark yield (g/m^2)	591	574	513	512	412	60***
Leaf yield (g/m^2)	151	154	165	147	145	n.s.
Leaf area index	4.23	4.30	4.61	4.12	4.01	n.s.
Node number	15.7	15.9	15.7	16.4	15.3	n.s.
Stem length (cm)	249	250	237	247	228	14*
Stem diameter (mm)	10.8	11.2	10.6	10.4	9.6	n.s.

Plant density:

Plant density did not vary significantly in the final three harvests. That is, water deficit conditions were insufficient to lead to plant death. However, there was evidence of leaf wilt in plants of the rainfed treatment at various times during the season.

Yield and yield components:

Significant treatment differences were apparent for total dry matter and stem yield in the fourth, fifth and final harvests (Table II.4.3, Figures II.4.2 and II.4.3).

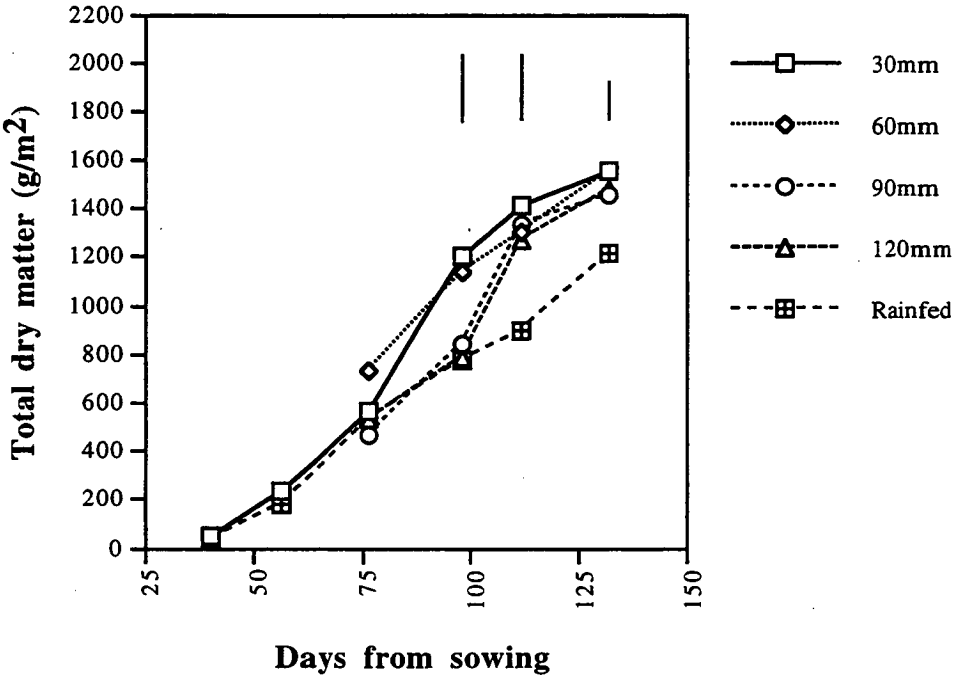


Figure II.4.2: Time response plot for total dry matter. The bars correspond to Fisher LSD values ($P<0.05$) for the final three harvests.

Significant treatment differences were first apparent at harvest 4 (day 98), with the total and stem dry matter yield of I30 and I60 exceeding those of the remaining treatments. There was an apparent delay in the response of I90 (1st irrigation on day 69) and I120 (1st irrigation on day 76) treatments to irrigation, with total dry matter and stem yield similar to that of the rainfed treatment at harvest 4 (98 DAS, Figures II.4.2 and II.4.3).

Following harvest 4, the growth rates associated with I90 and I120 increased sharply so that at harvests 5 and 6, the stem yield and total dry matter of the irrigated treatments were not significantly different, but each yielded more than the rainfed treatment. This increase in growth rate coincided with substantial rainfalls and higher temperatures in early January.

The percentage of bark in the stem appeared to decline with deficit to irrigation (Table II.4.3). The I30 and I60 treatments had significantly higher bark percentages

than the I120 and rainfed treatments. Similarly, I30 had a higher proportion than I90.

When translated into bark yield at final harvest, I30 and I60 yielded significantly more bark than the remaining treatments. Similarly, I90 and I120 were higher yelding than the rainfed treatment.

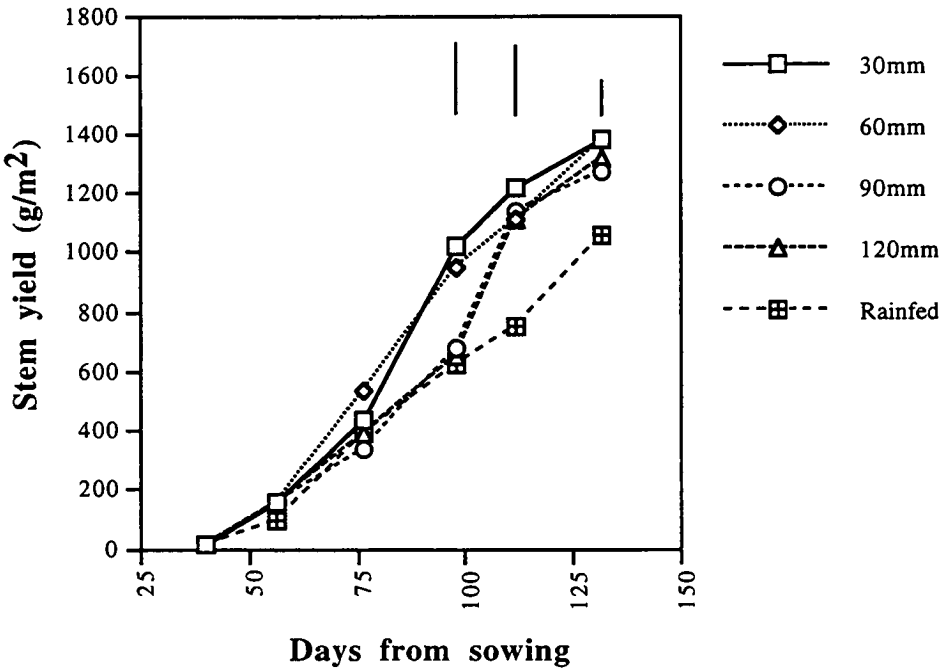


Figure II.4.3: Time response plot for stem yield. The bars correspond to Fisher LSD (P<0.05) for the final three harvests.

Leaf area production:

There were no significant differences between treatments for leaf area index or leaf yield at any of the harvests (Table II.4.3, Figure II.4.4). However, leaf area index for the 30 mm treatment was consistently greater than the rainfed treatment at all harvests. Furthermore, prior to flowering and the subsequent increase in leaf senescence (especially from male plants), LAI tended to decline with increased deficit.

While there was no apparent trend in node number across the irrigated treatments at each harvest, the node number for the rainfed treatment was consistently less than that for the irrigated treatments (final harvest data shown in Table II.4.3).

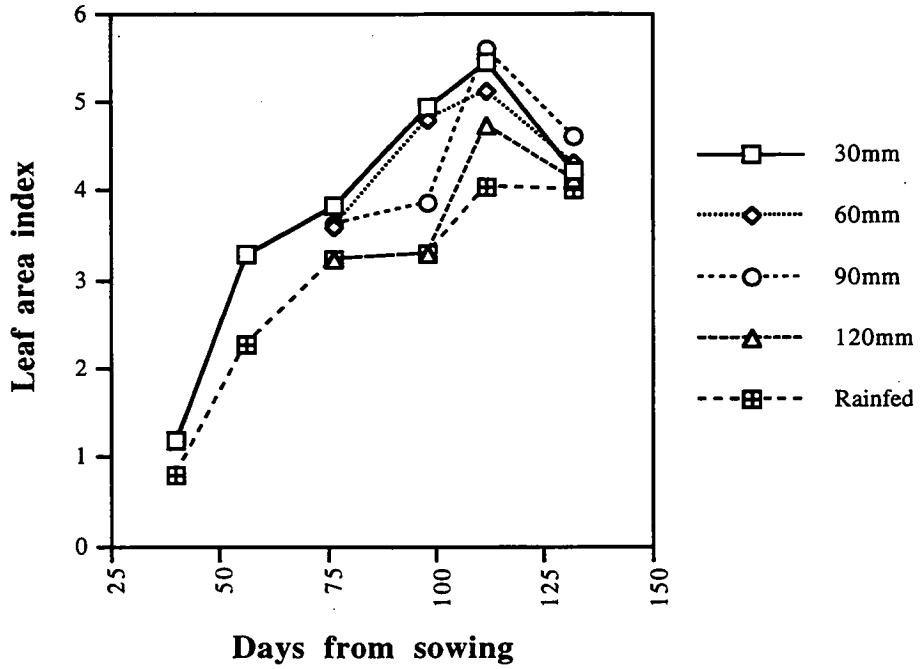


Figure II.4.4: Time response plot for leaf area index.

Stem dimensions:

Significant treatment differences were apparent for stem length in harvests 3,4,5 and 6 (Table II.4.3, Figure II.4.5). The response to irrigation was readily apparent at harvest 3, with I30 and I60 significantly taller than the recently irrigated I90 and unirrigated I120 and rainfed treatments. At harvests 5 and 6, the irrigated treatments were not significantly different in height but were all taller than the rainfed treatment. This response resembles the response of total dry matter and stem yield.

A similar response was apparent for stem diameter (Table II.4.3, Figure II.4.6). Stem diameter tended to decrease with increasing deficit at each harvest. At harvest 5, the irrigated treatments were not significantly different but had thicker stems than the rainfed treatment.

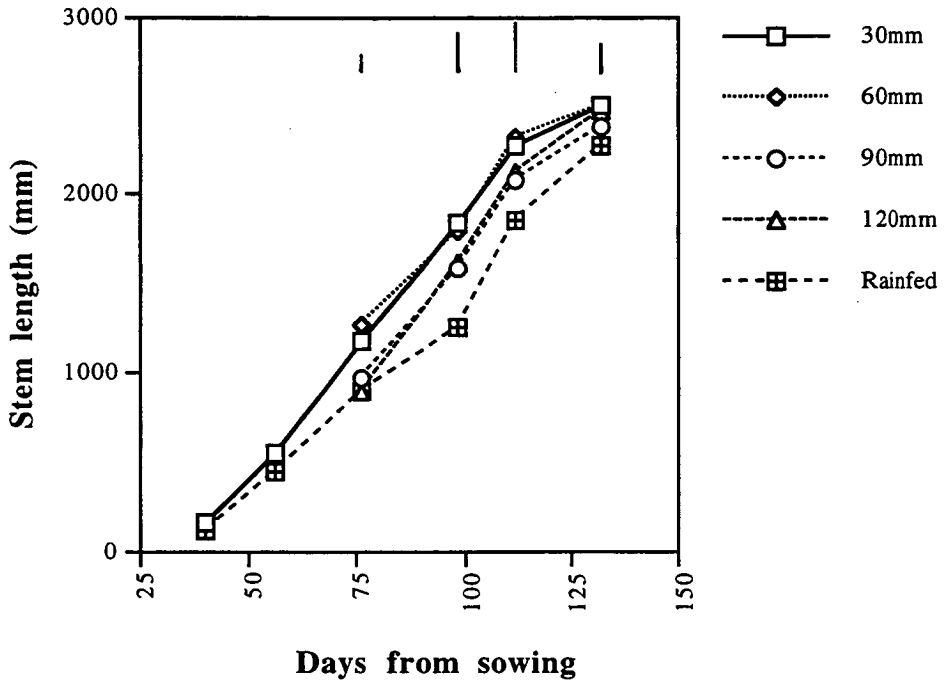


Figure II.4.5: Time response plot for stem length. The bars correspond to Fisher LSD (P<0.05) values for the final four harvests.

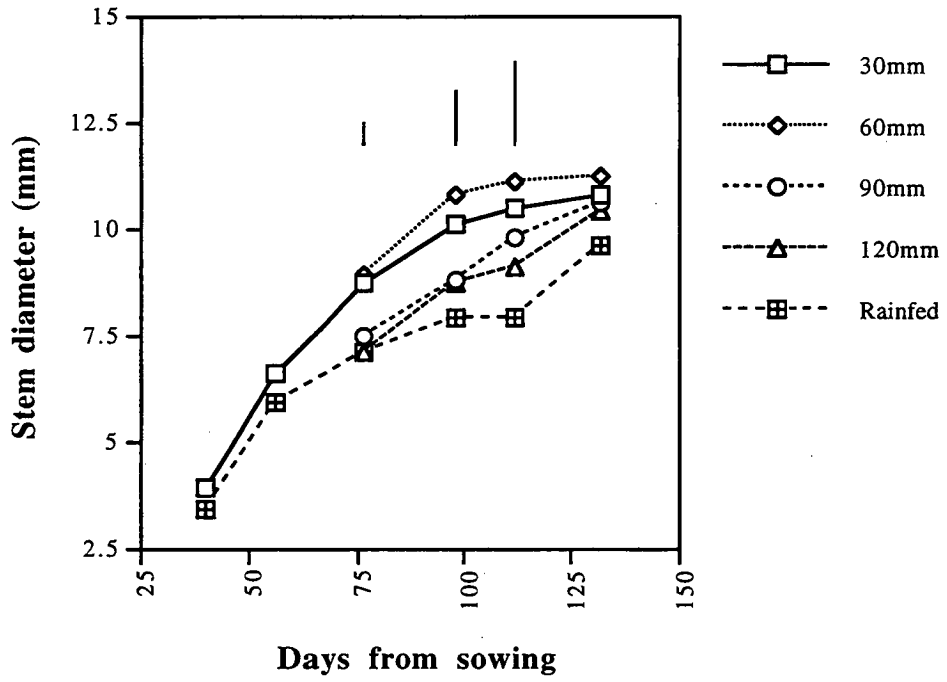


Figure II.4.6: Time response plot for stem diameter. The bars correspond to Fisher LSD (P<0.05) values for harvests 3, 4 and 5.

Flowering:

The time of flowering was taken as the 15th of January (112 days after sowing). There was no apparent difference between treatments.

Soil water extraction:

Figure II.4.7 shows patterns of volumetric soil water content (VSW%) recorded just prior to irrigation or rainfall events that returned the profile back to field capacity. These represent the maximum extent of crop water extraction for each irrigation treatment. The pattern corresponding to field capacity is also shown.

Across all treatments, soil water extraction was primarily confined to the upper 80-90 cm of the soil profile, with little extraction at greater depths. In the rainfed treatment, there was evidence of minor extraction down to at least 140 cm. The distribution of water extraction in three zones down to 100 cm (0-35, 35-55 and 55-100), averaged over the patterns selected for Figure II.4.7, are shown in Table II.4.4. The decline in total water content for each depth interval is expressed as a percentage of the water content at field capacity. With the exception of the 60 mm treatment, extraction decreased with increasing soil depth. This decrease appeared greatest for the 30 mm treatment, with just under two thirds of water extracted from the upper 35 cm of the profile. This may be attributable to a proliferation of roots in response to more frequent irrigation. In the other treatments, extraction appeared to shift into the 35 to 55 cm zone and, to a lesser extent, into the 55 to 100 cm zone.

Table II.4.4: Distribution of water extraction (%) in three depth intervals down to 100cm.

	Irrigation treatment:				
Depth zone (cm):	I30	I60	I90	I120	I0
0-35	63	53	51	57	56
35-55	22	23	30	28	27
55-100	15	24	19	15	17

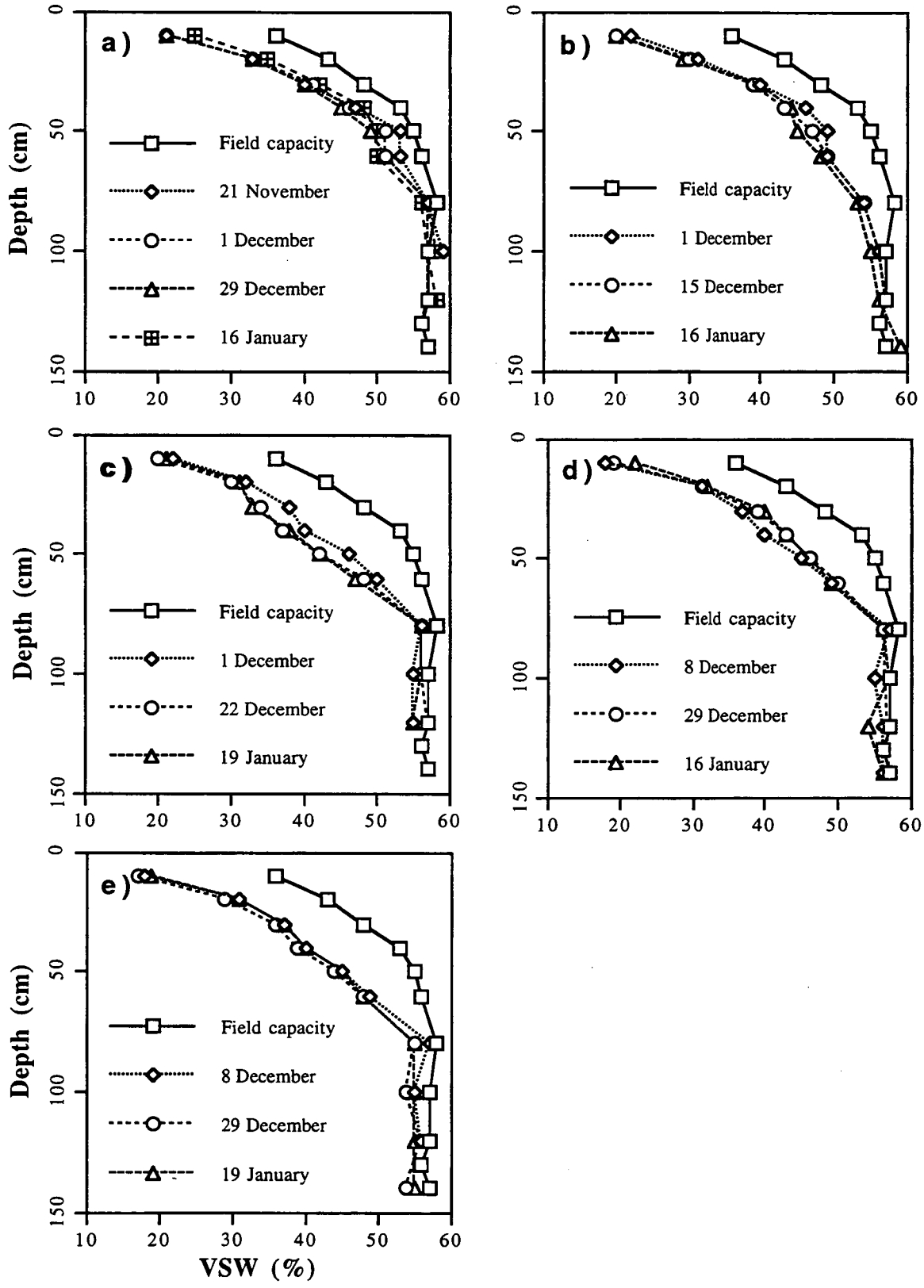


Figure II.4.7: Patterns of volumetric soil water content (%) with depth, at selected dates and at field capacity, for treatments: I30 (a), I60 (b), I90 (c), I120 (d) & I0 (e).

Seasonal water received / water consumption / water use efficiency:
The total amount of water received by each treatment is shown in Table II.4.5. This total is the sum of rainfall and irrigation, discounted for losses through runoff when the amount of rainfall exceeded the prevailing deficit. This loss was most prevalent with the more frequently irrigated treatments, as reflected by the similar totals for the 30, 60 and 90 mm deficit treatments. The greatest amount of water was received by the 60 mm treatment and the lowest by the rainfed treatment.

The change in water content between two N.M.M readings to a certain depth plus any intervening rainfall or irrigation amounts (discounted for runoff), gives a measure of the water consumed over that period. A sum of these periodic totals over the duration of the growing season gives the total water consumed. Seasonal water consumption to a depth of 90 cm is shown in Table II.4.5. In the period between sowing and the first N.M.M. reading, evapotranspiration was assumed equivalent to Class A pan evaporation. Dividing the mean stem dry weight by the total amount of water consumed through evapotranspiration, gives a measure of the water use efficiency for stem production (Table II.4.5).

Similar water use efficiencies of about 3 g/kg were obtained for the 30 mm, 120 mm and rainfed treatments, with lower values for the 60 mm and 90 mm treatments. The high values for the two driest treatments may indicate that the roots reached a greater depth and were able to extract stored water lower in the profile. It may also indicate that water was used more economically due to stomatal closure during periods of water stress (Salisbury & Ross 1985).

Table II.4.5: The effective amount of water received (mm) from irrigation and rainfall inputs, discounted for runoff; total amount of water consumed (mm) to a depth of 90 cm during the season; and water use efficiency for stem production.

Treatment:	Effective rain + irrigation (mm):	Water consumed to 90cm (mm):	Water use efficiency (g/kg Water):
30mm	419	468	3.0
60mm	440	535	2.6
90mm	429	524	2.4
120mm	348	422	3.1
Rainfed	277	359	2.9

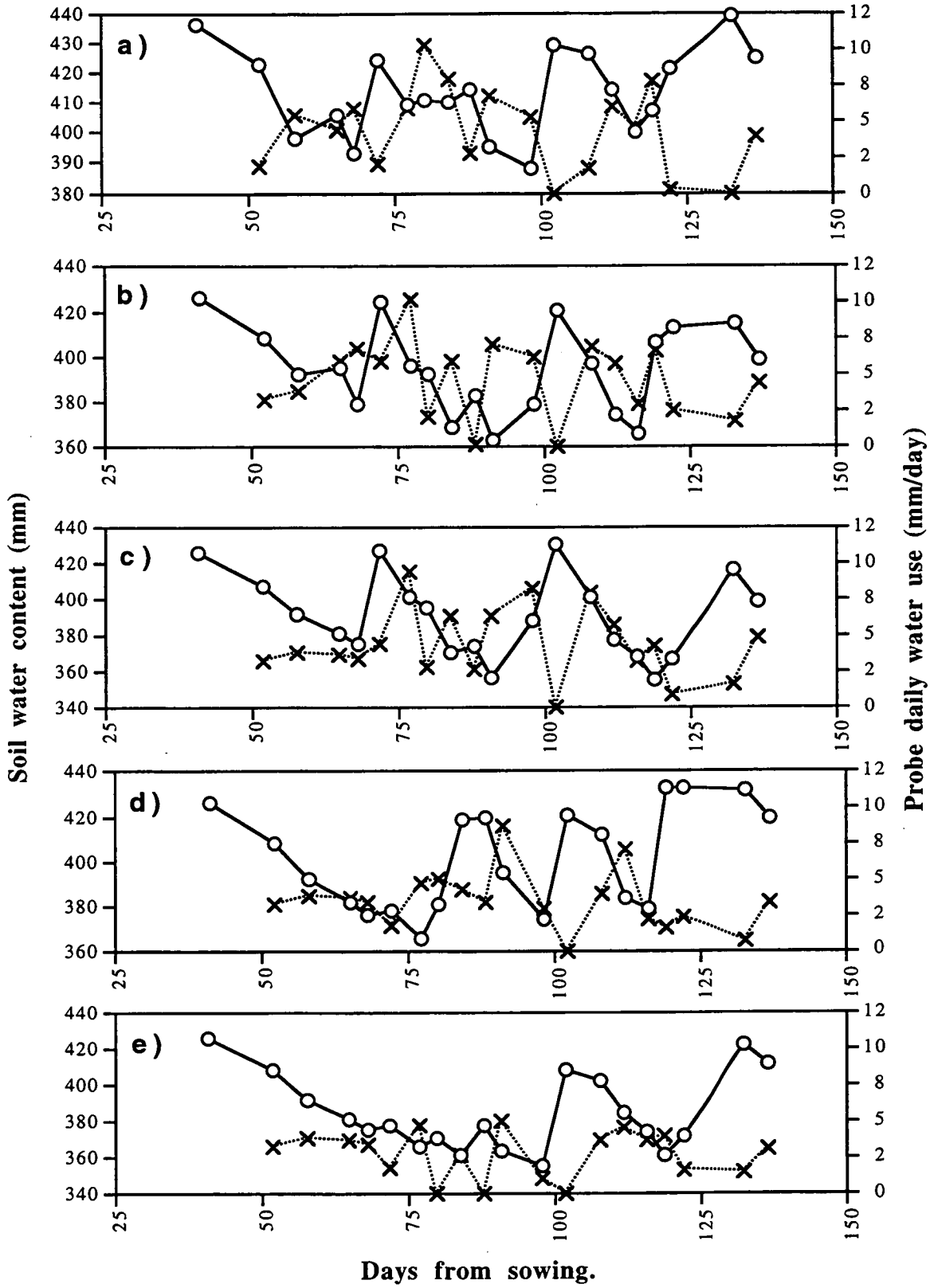


Figure II.4.8: Pattern of soil water content to 90cm (o, mm) and daily water use by the crop (x, mm/day) for treatments; I30 (a), I60 (b), I90 (c), I120 (d) & I0 (e).

Figure II.4.8 shows the pattern of soil water content and daily water consumption with time to a depth of 90 cm. Generally, increases in water consumption followed shortly after irrigation or rainfall events. Peak daily water consumption was similar across the four irrigated treatments at approximately 10 mm/day. The maximum for the rainfed treatment was about 5 mm/day. These maximums were reached during the month of December.

II.4.4 Discussion:

Significant stem yield differences were not apparent for irrigation regimes based on refill to field capacity at deficits down to 120 mm. Seasonal water consumption for this regime was approximately 420 mm. Maximum bark yield was obtained from regimes based on a 60 mm deficit or less (water consumption of 535 mm). The significant decline in stem bark content with increasing deficit has previously been observed for kenaf (Muchow & Wood 1980).

Whilst the yield of the rainfed treatment was reasonable, lower stem yields might be expected under average weather conditions at Forthside, when the seasonal rainfall total is less and January rainfall is less than half that received in this trial. In the absence of the large rainfall event in January, the stem yield (Figure II.4.3) for the rainfed treatment was likely to have only reached around 800-900 g/m^2. At Cambridge, in the drier southeastern portion of Tasmania, the average rainfall total for the same period is approximately 100 mm below that received at Forthside. Furthermore, the soils of this region are sandier and less retentive than the krasnozem soils in the northwest.

Begg and Turner (1976) report that a reduction in leaf area is a major morphological consequence of water stress. This is primarily brought about through a reduction in cell division and more importantly, a lessening in the rate of cell enlargement. Although differences between leaf area indices across the five treatments were not significant, there was evidence of a declining trend with increasing deficit. Across the irrigated treatments, this was most likely attributable to a decline in area per leaf rather than a decline in leaf (node) or plant number. A decline in leaf number may have contributed to the decline in leaf area between the irrigated and rainfed treatments.

Interestingly, there was a notable delay in the response of leaf area and dry matter production to the first irrigations for the 90 mm and 120 mm treatments. Eventually however, the growth rate increased sharply so that at harvests 5 and 6, differences between the irrigated treatments for yield and total dry matter were insignificant. This increase coincided with an increase in leaf area index. Begg and Turner (1976) report that a delay in the opening of stomata and the recovery of photosynthesis following alleviation of water stress, has been observed in a number of other species. Increases in growth rate following watering of previously stressed plants have been reported for tomato (Gates 1955) and kenaf (Muchow & Wood 1980). Ludlow (1975) and Ng *et al.* (1975) concluded that water stress suspended the ageing of physiologically young leaves and that upon rewatering, the photosynthetic rates of surviving leaves was greater than leaves of the same chronological age but comparable to those of the same physiological age.

II.5 Experiences with the harvesting of hemp.

II.5.1 Introduction:

The method of harvesting hemp varies between production centres. In countries where labour costs are low, the harvesting operation is often very labour intensive. In the more developed countries, high labour costs necessitate a mechanised approach. The renewed interest in hemp cultivation in such countries is fuelling developments in hemp harvesting and processing technology.

In France, two harvest systems are employed depending on whether the seed is to be harvested or not. Fibre only crops are cut at flowering with a mower/conditioner. After field drying for about four days, the moisture content is below 15% and the hemp is baled with a round baler. With the moisture content so low, the straw can be stored without significant deterioration over time. When harvested for both stem and seed, the upper part of the stem is cut and threshed with a combine when 75-80% of seed in the inflorescences are ripe (~early September). The remaining stems are then mown and laid down in a swathe to dry with occasional turning to encourage uniform drying and quality (Maeyer & Huisman 1994).

The system employed in England is similar to that used in France for the harvest of fibre hemp. The crop is first windrowed at flowering with a modified rape swather and then left to field dry and ret, prior to baling with a modified round baler. The leaves are shed naturally in the windrow prior to baling. The bales of whole stem are then stored prior to processing (Low 1995).

In the Netherlands, a wet harvest system was investigated whereby the stems were harvested green at flowering and ensiled for storage (Maeyer & Huisman 1994). They found that such anaerobic wet storage led to a significant decrease in fibre strength relative to dry storage. Furthermore, there were insufficient sugars in hemp to encourage spontaneous fermentation, thus requiring additives for successful ensiling. The system was abandoned in favour of a 'dry' system similar to that employed by the French and British.

It is believed that the relatively long, dry nature of the Tasmanian growing season is

well suited to a harvesting system where the straw is dried naturally in the field prior to collection. This chapter reports on the findings and observations from a preliminary harvesting trial on a small, semi-commercial dual purpose seed/fibre crop of hemp. A key objective was to assess the suitability of existing equipment currently used in the harvesting of other Tasmanian crops.

II.5.2 Materials and method:

The harvesting trial was conducted on a one hectare plot (50 m X 200 m) of hemp grown at Cambridge on the University of Tasmania Farm (42°50'S, 147°30'E). The crop was established in conjunction with members of the Tasmanian Hemp Company (P & F Harmsen). Seed of the cultivars Kompolti and USO 11 was sown at a rate of approximately 80 kg/ha using a combine drill. Sowing took place on September 30, 1994.

An NPK blend of 9:14:17 was predrilled at the rate of 300 kg/ha. This was followed by a top dressing of nitrogen in the form of Nitram and potassium as potash of ammonia, to bring the total level of applied nitrogen and potassium up to 100 kg/ha each.

The crop was irrigated on six separate occasions (30 mm of water each time) using a travelling gun irrigator. Observations were made of the approximate dates of flowering and seed maturity based on the method described in Chapter II.1.

The crop was harvested at seed maturity for both seed and fibre (Figure II.5.1.1). The shorter USO11 crop was mown at ground level with a draper style windrower (New Holland). A small area of the taller Kompolti crop was mown with a finger mower. An attempt was then made to remove seed from the mown crop using a combine harvester (John Deere) fitted with crop lifters. The remaining standing crop of Kompolti was direct headed (Figure II.5.1.3) and the straw then mown with the finger mower. A ground driven rake (Figure II.5.1.5) was used to move the straw into a windrow and to turn the windrow (on one occasion) to encourage uniform drying. Once field dried to approximately 15-18% moisture content, a round baler (Krone)(1.2 m diameter) was then used to collect the stem material (Figure II.5.6).

Figure II.5.1: (1) Trial crop of Kompolti at seed maturity. (2) Seed bearing heads of the same age showing the non-uniform nature of seed maturity. (3) Direct heading of seed using a combine harvester. (4) Windrowed crop with more uniform maturity and better seed retention. (5) Ground driven rake used to push the mown and dried straw into a windrow and to turn the crop. (6) Round baler used to collect the straw into 1.2 m diameter bales.

II.5.3 Results:

High rates of seedling emergence were apparent, with Kompolti emerging on October 10 and USO11 on October 11. USO11 flowered on November 11 and Kompolti on January 24. Seed maturity occurred approximately 6-7 weeks after the commencement of flowering. The average mature plant height was about 1 m for USO11 and 1.8-2 m for Kompolti.

Mowing/windrowing:

The draper style windrower was able to windrow most of the shorter USO11 crop, although some of the taller parts of the crop exceeded the width of the draper and hence tended to bunch up in front of the windrower. Modification to increase the width of the conveyor would be necessary to handle tall hemp crops. Such a modification could be readily performed on the auger type of windrower by fixing an extension plate on the auger frame. The width of the windrower and the throat (on belt styles) may also need modification, given the greater biomass of hemp and the need to carefully regulate the volume of the windrow to enable effective baling.

The finger mower was very effective at cutting the plant but clearly required an attachment to ensure that the stems fell parallel with one another. This would have improved the efficiency of subsequent raking and baling operations.

The ground driven rake was effective in windrowing and turning the mown (and then field dried) straw. An occasional problem was the tendency for the straw to tangle about the rotating rake wheel. Furthermore, the rake tended to pick up a certain amount of dirt, a potential contaminant in the papermaking process.

Seed harvest:

Seed removal from the standing crop proved difficult owing to the crop height being greater than the maximum height to which the combine harvester cutter bar could be raised (~180 cm). Consequently, more than the seed bearing portion of the stem was removed. Whilst this stem material passed through the combine without the tangling problems described below for the mown crop, taller hemp crops may create blockages. Most of the stem material that passed through the harvester was retrieved later during the baling operation.

A major limitation for efficient seed harvesting was nonuniformity in seed maturity, both within and between individual plants (Figure II.5.1.2). Furthermore, retention of mature seed was poor. Selecting the time for direct heading of seed involved a compromise between reducing the amount of green, immature seed and minimising seed losses from shedding. Consequently, the seed that was removed from the standing crop had a high moisture content (~26%) and had to be artificially dried prior to storage.

A further limitation with direct heading was the loss of stem material through trampling of the crop under the wheels of the combine. Some recovery may be possible by mowing the remaining stem at right angles to the direction of trampling, using a mower fitted with crop lifters.

Windrowing the crop promoted greater uniformity in terms of seed maturity and moisture content (Figure II.5.1.4). Furthermore, shedding losses were reduced in comparison with the more exposed standing crop. Attempts to use the combine harvester to harvest the seed from the windrowed crop proved difficult, owing to the tendency for the bark fibre to wrap about rotating elements within the harvester mechanism, especially the return auger and impeller. This resulted in severe blockage and brought a halt to the harvesting operation. Stem material which passed through the harvester was very tangled. This would create problems with baling and subsequent cutting of the stem or bark fibre to achieve the uniform fibre length necessary for paper production (Section V).

Baling:

Aside from a few small problems, baling was successfully conducted on April 15. Minor blockages occurred at the inlet to the baler between the pickup roller and encasing. This problem was largely overcome by reducing the groundspeed of the tractor to prevent the straw from banking up in front of the pickup roller. The optimum speed was measured at 4.5 km per hour. Reducing the volume of the windrow would further reduce the likelihood of blockage.

The inherent stiffness of the whole stem was presumably responsible for the tendency of some bales to have hollow centres. Conditioning of the stem material would help to create a tighter, denser bale with the added advantage of removing

residual leaf, seed and inflorescence contaminants prior to baling.

II.5.4 Discussion:

Whilst it proved possible to use existing equipment to harvest both the seed and fibre from a hemp crop, dual purpose cropping clearly has a number of limitations. Aside from the technical difficulties and losses in stem yield associated with seed removal described above, other potential limitations include: contamination from residual seed in the papermaking process, prolonged security risk and higher security costs, a decline in fibre quality between flowering and seed maturity (Heuser 1927, as cited by van der Werf 1991), and inadequate drying of the stem late in the season. Given the priority placed on fibre production (with seed as a by-product), a more appropriate system would involve separate seed and fibre crops managed in such a way as to optimise the yield and quality of each crop product.

The adoption of a harvesting system which uses a finger mower and rake to mow, windrow and turn the straw, would involve a number of machinery passes that would make harvesting costly and promote soil compaction. A better system would involve the use of a windrower to combine the operations of mowing and windrowing in one pass. Existing windrowers with narrow conveying platforms are unsuitable for the harvesting of tall hemp crops but could be readily modified to accommodate this crop.

The low rainfall/warm temperature conditions which normally prevail in Tasmania about the expected time of fibre harvest (January/February) are conducive to rapid field drying of the mown straw. While round balers were used in this trial, large square bales would improve the efficiency of transporting the harvested material to the processing facility.

Subsequent pulping trials at ANM identified that the bark fraction of the stem has the most potential in the papermaking process. Given the current absence of other markets for the core fraction, there are potential advantages in separating the bark and core fractions in the field. The core could be returned to the soil as an amendment and the bark fraction baled and transported to the paper mill. Graham (1995) reports on a field based, tractor driven hemp breaker developed in Germany (Gebr. Bahmer Maschinenbau GmbH). This machine achieves a decortication

efficiency of 80-90% from stem material with a moisture content of 12-15%. Stem material is picked up from windrows and can be either retted or unretted, although the efficiency of separation is improved with retting. The decorticated bark can then be pressed into either square or round bales.

Section III: Flax agronomy studies.

III.1 Evaluation of selected flax and linseed cultivars.

III.1.1 Introduction:

The objective of this study was to assess the potential of selected European and Australian flax and linseed cultivars for fibre and dual purpose fibre/seed production under Tasmanian conditions. The most highly ranked cultivar from these trials was used in further crop production studies.

Following a number of unsuccessful early attempts, a commercial Australian flax industry commenced in Victoria in 1935. The onset of the Second World War and an associated increase in demand for flax fibre led to rapid expansion, with production spreading to South Australia, Western Australia and Tasmania (Elliott 1959).

Fibre flax was first grown in Tasmania in 1940 and at its peak, the industry supported nine mills spread throughout the state (Elliott 1959). Cultivar trials were conducted in Tasmania between 1940 and 1941, incorporating a number of new Irish and some older more established European cultivars. Liral Crown, Liral Dominion, Liral Monarch and Concurrent were reported to have the highest straw yields (Tilt 1941). Concurrent and Liral Crown were the dominant commercial cultivars grown in Tasmania until the industry closed shortly after the end of World War Two.

In 1987, a number of oilseed cultivars were trialled at the Forthside Research Station in Tasmania's north west (R. Orr and S. Munford, unpublished data). This trial included a number of new edible Linola[1] lines bred for reduced alpha linolenic acid content (Green 1984, Green & Marshall 1984). In a report prepared for the Colac Economic Development Committee on the future potential of flax in Australia (Anonymous 1992), Linola was reported to have the most potential of all the oilseed cultivars. Linola is currently grown in Australia, Canada and the United Kingdom as a temperate oilseed crop (United Grain Growers 1995). The CSIRO has recently backcrossed Linola with the French fibre cultivar Ariane, to create a dual purpose Linola fibre line. This crossing program has only just been completed

[1] Linola is a registered trademark of CSIRO.

with insufficient seed currently available for field assessment. Performance is expected to be very similar to that of Ariane (A. Green pers. comm. 1996).

A preliminary field assessment of selected Australian and European flax cultivars was conducted at Cambridge in 1992 (W. Spielmeyer, unpublished data 1994). Five cultivars were included from the National Collection at Horsham, including: Standard, Flag, Currong, Liral Crown, and Banner. Another five cultivars were imported from Europe, including: Regina, Marina, Ariane, Viking and Belinka. Marina and Belinka were bred in the Netherlands, while Ariane and Viking originate from France. The results from this trial were generally inconclusive and it was decided to repeat the trial with the omission of the poor performing cultivars, namely Regina, Liral Crown and Currong.

In April of 1994, an approach was made by a German based pharmaceutical company, Fink GmbH (a subsidiary of SmithKline Beecham), to trial four dietetic linseed cultivars under Tasmanian conditions. These cultivars have been bred for high mucilage release from the seed. A layer of mucilage is formed on the outside of the seed when large epidermal mucilaginous cells swell upon exposure to water. Mucilage is used for the treatment of a range of digestive complaints. Despite the expected poor stem yields of these cultivars, they were included in a separate trial to assess their dual purpose potential.

III.1.2 Materials & method:

Design:

Two separate trials were established at the University of Tasmania Farm at Cambridge (42°50'S, 147°30'E). Trial 1 included seven flax cultivars: Belinka, Ariane, Viking, Marina, Standard, Banner and Flag. Trial 2 included four mucilage cultivars: Maxigold, Hella, Ceres and Kreola.

In each trial, a randomised complete block design was employed with four replicates. Each plot was 5 m long X 1.5 m wide.

Cultural methods:

The trials were sown on the October 13, 1994. Seed was sown to a depth of 2.5-3 cm at a row spacing of 15 cm using a 10 row cone seeder drill. The seeding

rate was 80 kg/ha for trial 1 and 60 kg/ha for trial 2.

Fertiliser, with an N:P:K ratio of 9:14:17 was applied at a rate of 300 kg/ha. A further 50 kg/ha of nitrogen was topdressed after emergence. The trial area was irrigated with overhead sprinklers on six occasions (~30 mm) from early November to mid January.

Plots were hand weeded on three separate occasions.

Data collection and analysis:

At seed maturity, a 2 m^2 sample was pulled from each plot for yield evaluation. Average stem dimensions were based on a subsample of 50 plants. Stem length refers to the total plant height from ground level to the top of the fruiting zone. Diameter was measured at the base of the stem.

The subsample was then recombined with the remainder of the sample and hand threshed to remove the seed and capsule fractions. The seed was subsequently cleaned and weighed for yield determination.

A second larger subsample was collected from the pre-weighed straw + root material and dried in an oven at 70 ^oC for 48 hours. The root fraction of this subsample was then removed in order to calculate the dry stem yield. The proportion of bark in the stem was determined from stem sections. Starting from about 10 cm above ground level, sections of approximately 15 cm in length were taken from 15 individual plants from each plot. The bark was peeled away from the core by hand and the relative proportions calculated from oven dry weights of each separated fraction.

The date of flowering was determined from regular observations after the appearance of floral buds. Flowering was taken as the time when 50% of the plants had one or more open flowers. The trials were harvested shortly after the stage of seed maturity was reached, ie when seeds were brown and rattling in the capsules (Turner 1987).

Analysis of variance tests were performed on total dry matter, stem yield, yield

components and stem dimensions using Systat 5.2.1 software. Means were compared using the Fisher LSD test with significance for P values less than 0.05.

III.1.3 Results:

Trial 1: European and Australian flax cultivars.

Final harvest results and times of flowering are shown in Table III.1.1.

Leaning was apparent with most of the cultivars following rainfall and irrigation events. With the exception of Standard, which lodged permanently, the other cultivars recovered quickly upon drying (Figure III.1.1.1).

Table III.1.1: Total dry matter (TDM), yield, yield components, stem dimensions, dates of flowering and harvest for trial 1. Fisher LSD figures shown with extent of significance of analysis of variance, ie *P<0.05, **P<0.01, ***P<0.001, n.s. not significant.

	Cultivar:							
	Marina	Ariane	Belinka	Viking	Flag	Banner	Standard	LSD 0.05
TDM (g/m^2)	1320	1176	1118	1094	875	858	883	108***
Stem yield (g/m^2)	883	841	714	714	512	473	488	86***
% Bark	31.0	30.2	29.7	36.2	27.8	28.3	27.7	n.s.
Bark yield (g/m^2)	262	257	205	262	145	133	132	43***
Seed (g/m^2)	218	184	187	199	191	156	189	n.s.
Stem length (cm)	76	76	71	68	60	60	57	7***
Stem diameter (mm)	2.5	2.4	2.4	2.3	2.0	2.0	1.8	0.3**
Flower date (1994)	10.12	13.12	6.12	9.12	9.12	5.12	7.12	-
Harvest date (1995)	11.2	11.2	11.2	11.2	11.2	12.2	11.2	-

Yield and yield components:

In terms of stem yield, the seven cultivars can be placed into three significantly different groups. Marina and Ariane were the highest yielding cultivars, followed by Belinka and Viking, and then a group containing the three Australian cultivars; Flag, Banner and Standard.

The percentage of bark in the stem did not differ significantly between cultivars due to the high degree of within treatment variability. However, the ranking of the four

Figure III.1.1: (1) 'Leaning' crop of flax during irrigation. (2) Weed infestation of 'dead nettle' (*Lamium* spp.) in flax crop (1995-96 flax seeding rate trial). (3) Secondary flowering of flax following late season rainfall.

European cultivars is similar to that reported in a trial conducted in the Netherlands (L. Vlaswinkel pers. comm. 1995). The high percentage of bark in Viking gave it an equivalent bark yield to Marina and Ariane.

Differences between seed yields were also insignificant. Results from the above mentioned Dutch trial showed that Ariane yielded substantially less seed than the other three European cultivars.

Development:

Emergence (50%) was relatively uniform across all cultivars and occurred on about the 18th of October.

All the cultivars commenced flowering within an eight day period in the first half of December. The extended vegetative period associated with Marina and Ariane may partly account for their higher stem yield.

Late rain slowed plant maturation and encouraged some secondary flowering (Figure III.1.1.3).

Stem dimensions:

A positive relationship between stem length and stem yield (Turner 1987) was clearly evident, with the ranking of mean stem length similar to that for stem yield. Similarly, stem length was closely related to flowering time. Marina and Ariane were significantly taller than Viking and the Australian cultivars. Belinka and Viking were significantly taller than Flag, Banner and Standard.

Stem diameter was generally larger in the European cultivars and followed the same rank order as total dry matter and stem yield.

Trial 2: Mucilage cultivars:

Final harvest results and times of flowering are shown in Table III.1.2.

Yield:

Kreola yielded significantly more stem than the other cultivars. Similarly, Hella and Ceres had higher stem yields than Maxigold. While not bred for stem yield, Kreola

apparently produced more stem weight than the Australian cultivars in trial 1.

The percentage of bark was not measured in this trial.

Maxigold and Ceres had significantly higher seed yields than Hella. The lowest seed yield was for Kreola. This was at least partly due to high temperatures and strong hot winds in early December. Many of the newly formed flower buds appeared to wilt and die in response to these conditions and follow-up rainfall triggered significant secondary flowering. These symptoms were not apparent in the other cultivars, presumably because of differences in the timing of floral initiation and hence susceptibility.

Table III.1.2: Total dry matter (TDM), yield, stem dimensions, dates of flowering and harvest for trial 2. Fisher LSD figures shown with extent of significance of analysis of variance, ie *P<0.05, **P<0.01, ***P<0.001.

	Cultivar:				
	Kreola	Hella	Ceres	Maxigold	LSD 0.05
TDM (g/m^2)	917	724	812	683	58***
Stem yield (g/m^2)	543	372	386	297	64***
Seed (g/m^2)	149	166	179	194	15**
Stem length (cm)	63	58	59	48	7**
Stem diameter (mm)	2.6	2.2	2.4	2.7	0.3*
Flower date (1994)	16.12	13.12	6.12	14.12	-
Harvest date (1995)	20.2	24.1	2.2	10.2	-

Stem dimensions:

As with trial 1, the trend in mean stem length was similar to that for stem yield. Maxigold was significantly shorter than all other cultivars.

Maxigold and Kreola had significantly larger stem diameters than Ceres and Hella.

Development:

Flowering of the four cultivars took place over a ten day period, commencing with Ceres on December 6 and ending with Kreola on the December 16. The positive relationships between flowering date and stem height and flowering date and stem

yield were not as apparent in this trial. In terms of stem height and yield, Ceres was comparable to Hella and superior to Maxigold, despite having flowered approximately a week earlier than these cultivars. Nevertheless, the latest flowering cultivar, Kreola had the highest stem yield.

III.1.4 Discussion:

The European flax cultivars yielded significantly more stem and bark fibre than the Australian flax cultivars. Of the former group, Ariane and Marina performed the best in terms of stem yield production, whilst Viking had comparable bark yields to these two cultivars. Non significant differences in seed yield prevented a ranking of cultivars for this parameter.

As expected, the mucilage cultivars were short and produced low stem yields. Maxigold, Ceres and Hella had stem yields less than half those of Marina and Ariane. Interestingly, seed yields were not superior to those for the flax cultivars. An inverse relationship between seed and stem yield was apparent within the mucilage cultivars, with Kreola having the highest stem yield and Maxigold and Ceres having the highest seed yields.

In selecting suitable cultivars for dual purpose cultivation, competition for available and suitable farming land in Tasmania, coupled with the potentially large fibre requirements of the newsprint mill, would place greater emphasis on optimising fibre yield rather than seed yield. Hence, the poor stem yields of the mucilage cultivars would suggest that they have little potential for dual purpose production. However, they may supply a future niche market for seed production.

The good performance of Ariane in these trials coupled with the market potential for Linola oil (Anonymous 1992), suggests that the Ariane/Linola cross developed by the CSIRO (A. Green pers. comm. 1996) offers considerable promise as a dual purpose cultivar. Given that the yield potential of the cross is likely to be very similar to Ariane (A. Green pers. comm 1996), Ariane was selected for use in subsequent flax field trials.

III.2 Seeding rate effects on flax performance.

III.2.1 Introduction:

The objective of this study was to investigate the influence of seeding rate on the fibre and seed yield of the cultivar Ariane.

References to optimum seeding rates for dual purpose seed/fibre production of flax are rare, as the crop is usually either grown specifically for fibre or, if grown as a dual purpose crop, management is directed toward optimising the yield and quality of the fibre component. Reported optimum rates for fibre production vary markedly depending on the intended end use of the fibre, growing conditions and other cultural factors.

Flax grown for fine linen yarn is normally grown at a much higher seeding rate than flax grown for paper and other industrial applications, which have less stringent requirements in terms of straw length, fineness and uniformity. The smaller seeding rates for industrial flax production reduce the risk of losses from crop lodging (Anonymous 1994).

Easson and Long (1992) investigated the response of spring sown flax to seeding rates ranging from 60-180 kg/ha in a series of trials in Northern Ireland. They observed a significant decline in percentage establishment, whereas straw yield, total fibre yield and incidence of lodging all increased with seeding rate. It was concluded that a plant density of about 1800 plants/m^2 (~120 kg seed/ha) was a suitable compromise between high fibre yield and the risk of lodging.

Rowland (1980) reported on the response of spring sown flax grown in Saskatchewan, Canada to seed rates of 50, 100 and 150 kg/ha. Straw yield increased with seeding rate while seed yield and oil content were not significantly affected. Height generally decreased with seeding rate.

Lower optimum seeding rates are reported for autumn sowings in Palampur, India (Guleria & Singh 1983). In trials with combinations of seeding rates (40, 60 and 80 kg/ha) and row spacings (15, 20 and 25 cm), the seed rate of 60 kg/ha gave the highest straw and fibre yield. Differences in the percentage of fibre in the stem were

not significant. Row spacings of 20 cm were found to be superior in terms of straw and fibre yields.

Lower optima were also reported for autumn and winter sown trials conducted in Tasmania (Tilt 1941). Separate trials were established at three sites with seeding rates of 56, 79, 101 and 123 kg/ha. At two of the sites, maximum straw yield was obtained with a rate of 101 kg/ha, while 79 kg/ha gave the highest yield at the third site. The lower yields at 56 and 123 kg/ha were attributed to branching and inter-plant competition, respectively. Lodging was felt to be a potential hazard for rates greater than 101 kg/ha.

The general response of crop yield to plant density (Ratkowsky 1983, Willey & Heath 1969) has previously been described in Chapter II.3 and will not be discussed further here.

III.2.2 Materials and method:

Design:

A randomised complete block design was employed with four replicates. Each plot was 1.6 m wide X 4 m long. In order to minimise edge effect, a buffer zone of one plot width (cv. Ariane) was sown on either side of the trial area.

The cultivar Ariane was sown at five seeding rates, including: 30, 50, 70, 90 and 120 kg/ha.

Cultural methods:

Seed was sown to a depth of approximately 2-3 cm and a row spacing of 13.5 cm using a 10 row cone seeder.

The trial was sown on September 26, 1995 at the Forthside Research Station (41°10'S, 146°40'E). Full emergence was achieved by the 10th of October.

Overhead sprinklers were used to irrigate the trial area. Scheduling was based on a cumulative deficit of 35 mm measured with a 'Class A' pan evaporimeter.

A blend of 9:14:17 NPK fertiliser (300 kg/ha) and zinc sulphite monohydrate

(10 kg/ha) was incorporated into the top 15-20 cm of the soil profile just prior to drilling. A further topdressing of nitrogen (40 kg/ha) was applied at 4-6 weeks.

The trial area was sprayed with MCPA (490 ml/ha) on November 4 (Stage 4-5, Turner 1987) to control an infestation of 'dead nettle' (*Lamium* spp.) (Figure III.1.1.2). The trial was also hand weeded in mid November.

Data collection & analysis:

Two sequential harvests of 0.25 m^2 were collected during the season (Table III.2.1), allowing 0.25 m of plot length as a buffer between each sample. The final harvest of 1 m^2 was collected at seed maturity.

Table III.2.1: Dates and days from sowing of sequential and final harvests.

Harvest:	Date:	Days from sowing:
H1	29.11.95	64
H2	2.1.96	99
H3	12.2.96	139

Total above ground fresh weight and plant density were measured from each sequential sample. A random selection of approximately 50 plants was then used for partition analysis and measurement of stem dimensions. Stem length and diameter were measured in the same way as described in Chapter III.1. The subsample plants were then partitioned and oven dried at 70 ^oC for 48 hours to determine stem yield and total dry matter results.

A slightly different approach was used for the final harvest sample. A representative subsample of 50 plants was first removed from the harvested sample to obtain measures of capsules per plant, seeds per capsule and stem dimensions. The rest of the harvested sample was hand threshed to remove the seed and capsule fractions. A seed cleaner was then used (on the recombined sample) to separate the seed for subsequent yield determination.

The percentage of bark in the stem was determined by manual separation of stem sections from 15 individual plants using the method described in Chapter III.1.

Regression analysis was performed using Systat 5.2.1 software. Asymptotic yield density relationships were modelled by fitting Shinozaki and Kira (1956) equations to reciprocal of yield per plant versus density plots.

Analysis of variance tests were performed on total dry matter, yield, yield component and stem dimension results from the final harvest. Means were compared using the Fisher LSD test with significance for P values less than 0.05.

III.2.3 Results:

Plant density:

There was no apparent trend in plant density with time for any of the treatment seeding rates. The regression analysis employed below uses an average density calculated from sequential and final harvest counts (Table III.2.2).

Table III.2.2: Treatment seeding rates and corresponding plant densities averaged across the three sequential harvests.

Seeding rate (kg/ha):	Plant density (plants/m^2):
30	498
50	807
70	1061
90	1344
120	1932

Total dry matter and stem yield:

Table III.2.3: Total dry matter, yield, yield components and stem dimensions for the final harvest (H3). Fisher LSD figures shown with extent of significance of analysis of variance ie *P<0.05, **P<0.01, ***P<0.001, n.s. not significant.

Seeding rate (kg/ha):	30	50	70	90	120	LSD 0.05
Total D.M. (g/m^2)	920	893	928	954	1055	n.s.
Stem yield (g/m^2)	567	564	579	617	710	n.s.
Bark percentage	33.2	35.3	34.5	37.3	33.4	n.s.
Stem length (cm)	83.1	80.5	73.0	70.4	72.9	8.1**
Stem diameter (mm)	2.7	2.5	2	1.7	1.5	0.4***
Capsule no./plant	8.1	6.3	4.1	2.5	1.9	1.7***
Seed no./capsule	8.9	9.1	9	9.1	9.1	n.s.
TSW (g)	6.2	6.2	6	5.9	6	n.s.
Seed yld. (g/m^2)	202	196	195	187	189	n.s.

Analysis of variance tests on final harvest total dry matter, stem yield and bark percentage did not indicate significant treatment differences (Table III.2.3).

The apparent increasing trend in total dry matter and stem yield with seeding rate was investigated by regression analysis. Shinozaki and Kira (1956) equations gave excellent fits to plots of reciprocal mean yield per plant versus plant density at each of the three harvests (Table III.2.4). This is indicative of an asymptotic response of yield per unit area to plant density.

Seed yield and seed yield components:

Seed yield, thousand seed weight (TSW) and seed number per capsule did not change significantly with seeding rate. Capsule number per plant generally decreased as seeding rate increased (Table III.2.3 & Table III.2.4).

Plant dimensions:

At final harvest, stem diameter was significantly larger for the 30 and 50 kg/ha treatments (Table III.2.3). Regression analysis gave significant linear declines in stem diameter with the logarithm of plant density for each harvest (Table III.2.4).

Stem length declined linearly with the logarithm of plant density for the first and final harvests (Table III.2.4).

Table III.2.4: Fitted reciprocal equations for total dry matter and stem yield per plant (W), capsule number per plant (C), stem length (L) and diameter (D) versus plant density (ρ, plants/m^2) for each harvest. The significance of the linear models is identified by the asterisks (P<0.05 *, P<0.01**, P<0.001***).

Total dry matter (g/m^2):

Harvest:	Equation:	R^2
H3	$W^{-1}=0.161+0.001\rho$	0.98***
H2	$W^{-1}=0.499+0.001\rho$	0.97**
H1	$W^{-1}=3.534+0.003\rho$	0.98***

Stem yield (g/m^2):

Harvest:	Equation:	R^2
H3	$W^{-1}=0.377+0.001\rho$	0.97**
H2	$W^{-1}=0.785+0.001\rho$	0.97**
H1	$W^{-1}=5.745+0.005\rho$	0.97**

Capsule number per plant:

Harvest:	Equation:	R^2
H3	$C^{-1} = 3.1X10^{-4}\rho-5.6X10^{-2}$	0.96**

Stem length (cm):

Harvest:	Equation:	R^2
H3	$L=152.5-252.8\log_{10}\rho$	0.79*
H1	$L=39.6-36.2\log_{10}\rho$	0.78*

Stem diameter (mm):

Harvest:	Equation:	R^2
H3	$D=8.3-2.1\log_{10}\rho$	0.92*
H2	$D=9.1-2.3\log_{10}\rho$	0.94**
H1	$D=5.5-1.1\log_{10}\rho$	0.92**

Development:

The timing of key development events (Table III.2.5) did not appear to differ across the five seeding rate treatments.

Table III.2.5: Approximate commencement dates for key growth stages (GS) (Turner 1987).

Development stage:	Date:	Days from sowing:
Flowering (GS7)	16.12.95	81
Green capsule (GS10)	3.1.96	99
Seed ripe (GS12)	5.2.96	132

III.2.4 Discussion:

Of the various seed yield components, only the number of capsules per plant was significantly affected by seeding rate. The proportional decline in capsule number was similar to the proportional increase in plant density. That is, doubling the density resulted in an approximate halving of the capsule number. In the absence of significant changes in the other seed yield components of thousand seed weight and seed number per capsule, seed yield did not change significantly with seeding rate. Similar trends were apparent across the seeding rate treatments of the irrigation X sowing date X seeding rate trial at Cambridge, discussed in the following chapter.

Differences in stem yield were small and insignificant ($P<0.05$) across the range of seeding rates trialled in this experiment. However, there was an increasing asymptotic trend in total dry matter and stem yield with seeding rate. This was supported by the excellent fit of Shinozaki and Kira equations across the three harvests.

Selection of the optimum seeding rate may require a compromise between achieving maximum yield and limiting losses from lodging. Leaning was apparent in the 90 and 120 kg/ha treatment plots following heavy rain shortly after flowering. While most plants recovered upon drying, a percentage of the plants remained permanently lodged. Sowing date and irrigation are also likely to influence the

occurrence of lodging and hence the selection of optimum seeding rate. These influences were investigated in a trial conducted in the following season. The findings of this trial are discussed in the following chapter.

III.3 Sowing date effects on flax performance in Tasmania.

III.3.1 Introduction:

Time of planting studies and commercial plantings conducted in Tasmania during the early 1940's, suggest a favoured sowing period from the beginning of March to the first week of April (Tilt 1941, Wilson 1944, Hansen 1945). Delays in sowing beyond this period were found to increase the risk of frost damage, to which flax was found to be very susceptible in the early stages of growth. Resistance to successive heavy frosts required strong root establishment and fair top growth (approximately 20 cm high). However, such early sowings limited the opportunity to germinate weed seeds and subsequently destroy the emerged weed plants before sowing the flax crop (Wilson 1944). Under favourable seasonal conditions, spring sowings were found to produce satisfactory crops, but the percentage of failures was relatively high (Hansen 1945). Failure was primarily attributed to insufficient soil moisture at sowing and low rainfall from October to December. Tilt (1941) reported that compared to later sowings in September and October, sowings in early July and August were more established and better able to withstand the dry conditions experienced in October and November. Weed competition was also found to be more severe on the later sown plots. The response of seed yield to sowing date was not reported in any of these early references.

In more recent trials conducted at Forthside with the linseed variety Glenelg (Orr and Munford, unpublished data 1991), seed yield tended to decline with sowing date from August 15 to November 11.

Sowing date selection should also take into account the sensitivity of this species to frost and high temperatures at the flowering stage. Plants will often compensate for frost damage by branching and the formation of new buds. Provided growing conditions are good, the reduction in seed yield will be minor. High temperatures (approximately 30 ^{o}C) during flowering and seed development have been reported to reduce seed number, seed size and oil content (Green *et al.* 1994).

The potential for lodging and the susceptibility of the crop to waterlogging (Elliott 1959) may also influence sowing date selection. Late winter or spring sowing of

linseed is suggested in high rainfall areas of Australia (Green *et al.* 1994).

Linseed is susceptible to water stress at the seedling stage, at flowering and during early seed development (Green *et al.* 1994). Water stress during the latter two phases can lead to premature senescence and hence limit the period of oil synthesis and deposition in the seed (Turner 1987). In areas where water is likely to be limiting at these stages, irrigation is suggested from budding through until late grain fill. Later watering may cause secondary flowering and hence uneven ripening (Green *et al.* 1994).

The objective of this study was to investigate the response of dual purpose flax production to sowing date in Tasmania. Interactions between sowing date and cultivar, seeding rate and irrigation treatments were also investigated.

III.3.2 Materials and method:

Design and treatments:

Separate sowing date trials were conducted at Forthside (41°10'S, 146°40'E) (Trial 1) and Cambridge (42°50'S, 147°30'E) (Trial 2) in the 1994-95 and 1996-97 seasons respectively. The Forthside trial considered the response of two cultivars to a range of spring sowing dates. Interactions with irrigation and seeding rate were investigated in the second trial at Cambridge (Table III.3.1).

The trials were established as split plot designs. In trial 1, sowing dates occupied the plot stratum and cultivars the split plot stratum. There were four replicates of each treatment combination and the plot size was 12 m^2. In trial 2, irrigation treatments occupied the plot stratum, sowing dates the split plot stratum and seeding rates the split split plot stratum. Ariane was the cultivar used in this second trial. There were three replicates of each treatment combination and the plot size was 4.5 m^2. In order to minimise edge effect, a buffer zone of one plot width (cv. Ariane) was sown around each trial.

Table III.3.1: Treatment combinations for the two trials.

Trial 1:	Trial 2:
Forthside 1994-95:	**Cambridge 1996-97:**
2 Cultivars:	4 Sowing dates:
Ariane	16.5.96 (SD1)
Belinka	25.6.96 (SD2)
4 Sowing dates:	14.8.96 (SD3)
30.8.94 (SD1)	17.9.96 (SD4)
21.9.94 (SD2)	3 Seeding rates:
10.10.94 (SD3)	80 kg/ha (SR1)
24.10.94 (SD4)	110 kg/ha (SR2)
	140 kg/ha (SR3)
	Irrigation:
	Rainfed
	Irrigated

Cultural methods:

Seed was sown to a depth of approximately 2 cm using a 10 row cone seeder with 15 cm row spacings. Trial 1 was sown at a seeding rate of 60 kg/ha.

Fertiliser with an N:P:K ratio of 9:14:17 was applied at a rate of 300 kg/ha. A further 50 kg/ha of nitrogen was topdressed after emergence. In trial 2, soil tests suggested deficiencies in calcium. Consequently, dolomite was applied as a topdressing shortly after emergence at a rate of 80 kg/ha.

In each trial, weeds were removed by hand up until flowering.

Trial 1 was irrigated with overhead sprinklers on six occasions (~30 mm) from early November to mid January. The irrigated treatments of trial 2 were watered using a drip irrigation system. Five lengths of the 12 mm drip tubing were positioned across each irrigated plot at 30 cm spacings. Drip points spaced at 30 cm intervals along

each tube delivered 2 L of water per hour. Approximately 30 mm of water was applied to the irrigated treatments on five separate occasions from early November to mid January.

Figure III.3.1 shows the seasonal and long term average rainfall data for Cambridge. Data were collected at the Hobart airport, situated approximately 6 km from the trial site.

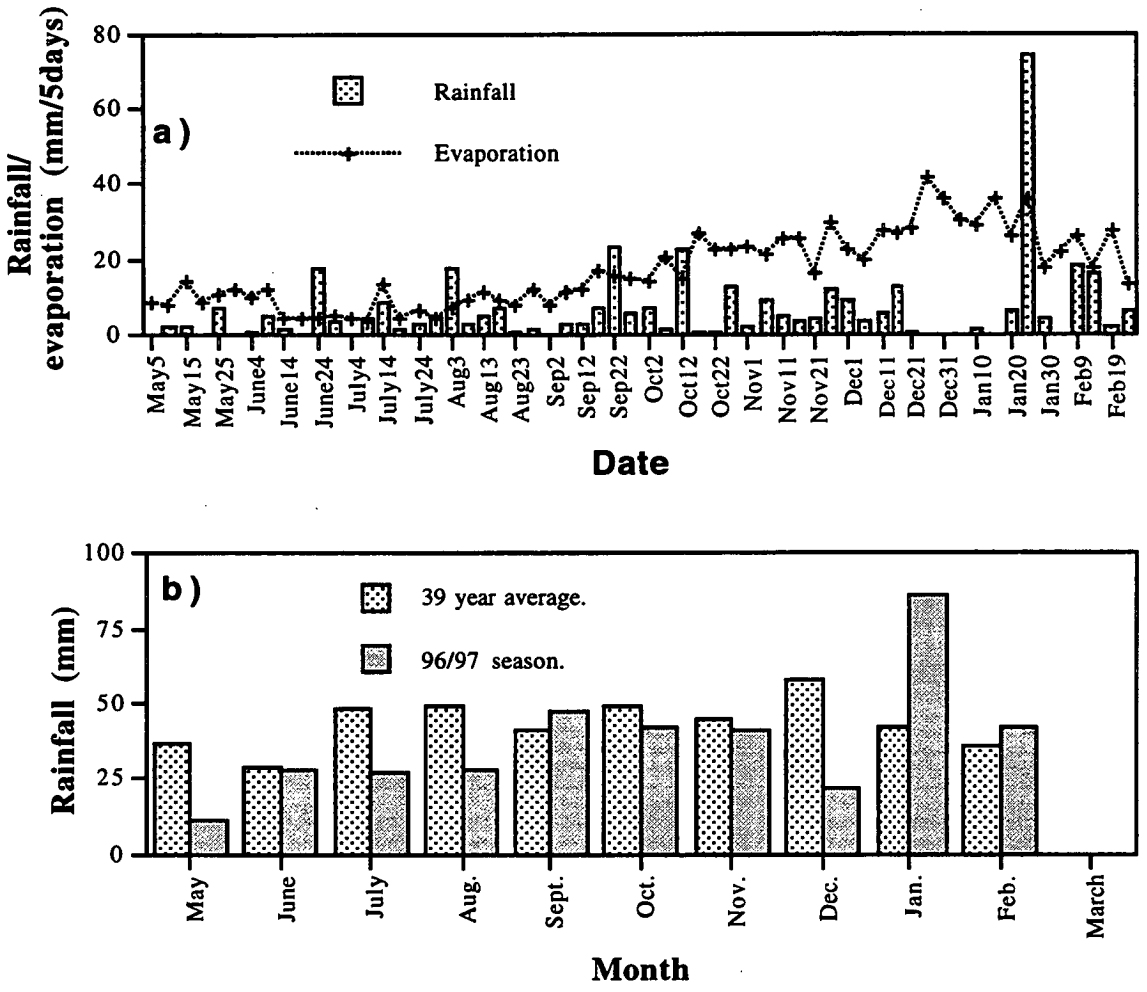


Figure III.3.1: (a) Total rainfall and Class A pan evaporation for five day periods from 5/5/96 to 19/2/97. (b) Monthly average rainfall totals from 1958-1996 and 1996-97 season monthly totals. Figures were collected at the Hobart Airport.

Data collection & analysis:

Trial 1: Sowing date X cultivar trial, Forthside:

Sequential harvests of 0.25 m^2 were collected at regular intervals for total dry matter determination, allowing 0.25 m of plot length as a buffer between each

sample. At seed maturity, a 2 m^2 sample was pulled from each plot for yield evaluation.

Average stem dimensions were based on a subsample of 50 plants. The method adopted was the same as that described in Chapter III.1.

The subsample was then recombined with the remainder of the sample and hand threshed to remove the seed and capsule fractions. The seed was subsequently cleaned and weighed for yield determination.

A second larger subsample was collected from the pre-weighed straw + root material and dried in an oven at 70 ^oC for 48 hours. The root fraction of this subsample was removed in order to calculate the above ground dry stem yield. The percentage of bark in the stem was determined by manual separation of stem sections from 15 individual plants of similar diameter, using the method described in Chapter III.1.

The date of flowering was determined from regular observations after the appearance of floral buds. Once again, the method was the same as that described in Chapter III.1.

Trial 2: Irrigation X sowing date X plant density trial, Cambridge:
Data were derived from a final harvest sample collected at seed maturity. The procedure was similar to that described above for trial 1. In addition, the components of seed yield were measured, ie capsule number per plant, seed number per capsule and thousand seed weight (TSW). Seed counts were made using a Pfeuffer Contador seed counter.

Analysis of variance tests were performed using Systat 5.2.1 software. Means were compared using the Fisher LSD test with significance for P values less than 0.05.

Table III.3.2: Final harvest results for trial 1.
A and B denote Ariane and Belinka respectively.
Fisher LSD figures shown with extent of significance, ie *P<0.05, **P>0.01, ***P<0.001, n.s. not significant.

	Stem length (cm)			**Stem diameter (mm)**			**Total D.M. (g/m^2)**			**Stem yield (g/m^2)**			**Seed yield (g/m^2)**		
	A	B	Av.	A	B	Av.	A	B	Av.	A	B	Av.	A	B	Av.
SD1: 30.8.94	98	87	93	2.5	1.9	2.2	1202	1088	1145	782	689	736	221	218	220
SD2: 21.9.94	99	89	94	2.2	1.8	2.0	1205	993	1099	801	653	727	216	186	201
SD3: 10.10.94	97	99	98	2.2	2.0	2.1	1120	1237	1179	749	751	750	197	267	232
SD4: 24.10.94	97	94	96	2.3	2.2	2.3	1126	982	1054	717	613	665	208	186	197
Average	98	92		2.3	2.0		1163	1075		762	677		211	214	
Interaction	n.s			n.s			n.s			n.s			n.s		
Main S.D. effect	n.s			n.s			n.s			n.s			n.s		
Main cv. effect	3.9***			0.2***			n.s			66**			n.s		

III.3.3 Results:

Trial 1: Sowing date X cultivar trial, Forthside:

Final harvest results from trial 1 for total dry matter, yield, yield components and stem dimensions are shown in Table III.3.2.

Lodging:

Temporary leaning was observed after rainfall and irrigation events late in the season. However, plants generally recovered quickly upon drying.

Dry matter distribution:

Figure III.3.2 shows the trend in total dry matter with time for the treatment combinations in trial 1. Linear phase growth rates were similar for each sowing date treatment. While the peak total dry matter for Ariane sowings was generally higher than for Belinka, the final harvest values were similar.

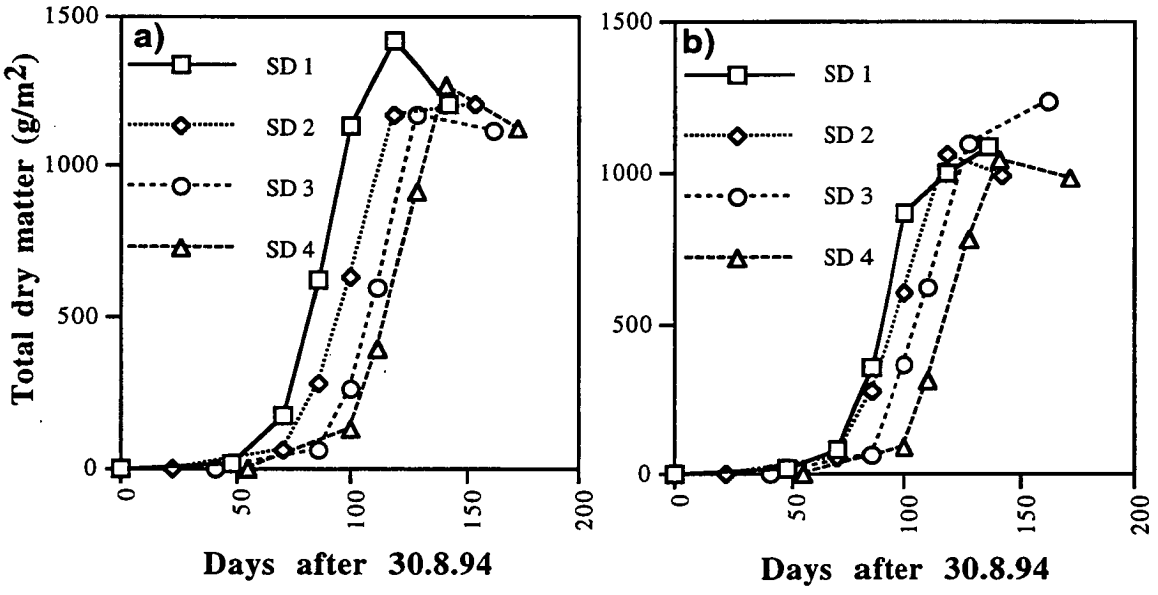


Figure III.3.2: Total dry matter versus time from the first sowing date for Ariane (a) and Belinka (b) in trial 1.

Stem yield & dimensions:

Differences in stem yield, stem length and diameter with sowing date were not significant. Ariane had significantly taller and thicker stems and yielded more stem than Belinka.

Seed yield & seed yield components:

Seed yield differences between sowing dates and the two cultivars were not significant.

Flowering:

Ariane commenced flowering approximately 2-3 days before Belinka (Table III.3.3). Flowering was delayed by progressively later sowing. The delay in flowering time was approximately half that of the delay in sowing date and enabled later sown plots to catch up under more favourable radiation and temperature conditions. This is reflected by insignificant differences in stem and seed yields, and the similarity in thermal time accumulations across the four sowing date treatments.

Table III.3.3: Date of flowering, calendar days and thermal time (above a base temperature of 1 °C) from sowing to flowering for trial 1.

Trial 1: Forthside 1994-95:

	Date:		Calendar Days:		Thermal time:	
	A	B	A	B	A	B
SD1	28.11.94	25.11.94	90	87	826	790
SD2	9.12.94	7.12.94	79	77	816	787
SD3	19.12.94	16.12.94	70	67	822	788
SD4	26.12.94	24.12.94	63	61	782	753

Trial 2: Irrigation X sowing date X plant density trial, Cambridge:

Final harvest results from trial 2 for plant density, total dry matter, yield, yield components and stem dimensions are shown in Table III.3.4.

Lodging:

Leaning and permanent lodging was apparent in the irrigated plots of the higher two seeding rates in the first three sowing dates. Lodging was most pronounced in SD2 plots. Minor lodging was also evident in some of the rainfed plots of SD1 and SD2.

Table III.3.4: Final harvest results for trial 2.
Fisher LSD figures shown with extent of significance, ie *P<0.05, **P>0.01, ***P<0.001, n.s. not significant.

Plant density (plants/m^2)

Rainfed:

	Sowing date:				
	SD1	*SD2*	*SD3*	*SD4*	Average
SR1	1023	809	947	1068	962
SR2	1357	1061	1108	1174	1175
SR3	1434	1179	1454	1660	1432
Average	1271	1016	1170	1301	

Irrigated:

	Sowing date:				
	SD1	*SD2*	*SD3*	*SD4*	Average
SR1	881	842	793	920	859
SR2	1184	925	994	1087	1048
SR3	1349	1074	1057	1196	1169
Average	1138	947	948	1068	

Main irrigation effect:	170**
Main sowing date effect:	255*
Main seeding rate effect:	166***
I X D interaction:	n.s
I X R interaction:	n.s
D X R interaction:	n.s
I X D X R interaction:	n.s

Stem yield (g/m^2)

Rainfed:

	Sowing date:				
	SD1	*SD2*	*SD3*	*SD4*	Average
SR1	839	547	482	477	586
SR2	1112	596	517	496	680
SR3	846	587	585	512	633
Average	932	577	528	494	

Irrigated:

	Sowing date:				
	SD1	*SD2*	*SD3*	*SD4*	Average
SR1	970	770	674	671	771
SR2	1136	932	1022	772	966
SR3	1079	793	922	747	885
Average	1062	832	873	730	

Main irrigation effect:	115***
Main sowing date effect:	157***
Main seeding rate effect:	76***
I X D interaction:	*
I X R interaction:	n.s
D X R interaction:	*
I X D X R interaction:	n.s

Bark %

Rainfed:

	Sowing date:				
	SD1	*SD2*	*SD3*	*SD4*	Average
SR1	40	38	35	34	37
SR2	41	39	34	36	38
SR3	37	37	37	35	37
Average	38	38	35	35	

Irrigated:

	Sowing date:				
	SD1	*SD2*	*SD3*	*SD4*	Average
SR1	38	36	37	35	37
SR2	37	39	34	33	36
SR3	41	38	36	34	37
Average	39	38	36	34	

Main irrigation effect:	n.s
Main sowing date effect:	1.9***
Main seeding rate effect:	n.s
I X D interaction:	n.s
I X R interaction:	n.s
D X R interaction:	n.s
I X D X R interaction:	n.s

Table III.3.4 (cont.)

Stem length (cm)

Rainfed:

	Sowing date:				
	SD1	*SD2*	*SD3*	*SD4*	Average
SR1	91	82	81	73	82
SR2	97	84	84	78	86
SR3	82	75	74	72	76
Average	90	80	80	74	

Irrigated:

	Sowing date:				
	SD1	*SD2*	*SD3*	*SD4*	Average
SR1	96	101	103	94	99
SR2	93	103	108	96	100
SR3	94	96	103	93	97
Average	94	100	105	94	

Main irrigation effect:	2 * * *
Main sowing date effect:	9 * *
Main seeding rate effect:	5 *
I X D interaction:	* * *
I X R interaction:	n.s
D X R interaction:	n.s
I X D X R interaction:	n.s

Stem diameter (mm)

Rainfed:

	Sowing date:				
	SD1	*SD2*	*SD3*	*SD4*	Average
SR1	2.6	2.8	2.4	2.2	2.5
SR2	2.4	2.5	2.2	2.1	2.3
SR3	2.1	2.1	1.8	1.8	2
Average	2.4	2.5	2.1	2	

Irrigated:

	Sowing date:				
	SD1	*SD2*	*SD3*	*SD4*	Average
SR1	3.4	2.8	2.8	2.9	3
SR2	3	2.8	2.7	2.5	2.8
SR3	2.5	2.5	2.4	2.4	2.5
Average	3	2.7	2.6	2.6	

Main irrigation effect:	0.3 * * *
Main sowing date effect:	0.2 * *
Main seeding rate effect:	0.2 * * *
I X D interaction:	n.s
I X R interaction:	n.s
D X R interaction:	n.s
I X D X R interaction:	n.s

Capsule number per plant

Rainfed:

	Sowing date:				
	SD1	*SD2*	*SD3*	*SD4*	Average
SR1	6.4	6.1	4.4	6.3	5.8
SR2	4.9	4.4	4.5	5.4	4.8
SR3	5.2	4.3	2.9	3.2	3.9
Average	5.5	4.9	3.9	5	

Irrigated:

	Sowing date:				
	SD1	*SD2*	*SD3*	*SD4*	Average
SR1	17.1	8.4	5.9	6.6	9.5
SR2	9.1	7.6	5.3	4.4	6.6
SR3	8.4	5.5	3.7	3.4	5.3
Average	11.5	7.2	5	4.8	

Main irrigation effect:	2.7 * * *
Main sowing date effect:	2.0 * * *
Main seeding rate effect:	1.1 * * *
I X D interaction:	* * *
I X R interaction:	*
D X R interaction:	*
I X D X R interaction:	*

Table III.3.4 (cont.)

Seed number per capsule

Rainfed:

	Sowing date:				
	SD1	*SD2*	*SD3*	*SD4*	Average
SR1	8.8	8.3	6.1	7.3	7.6
SR2	7.3	7.8	6.6	6.2	7
SR3	8.1	8.2	6.4	6.6	7.3
Average	8.1	8.1	6.4	6.7	

Irrigated:

	Sowing date:				
	SD1	*SD2*	*SD3*	*SD4*	Average
SR1	7.1	6.4	6.3	5.6	6.4
SR2	5.8	6.6	6.4	5.3	6
SR3	5.7	5.3	5.6	4.9	5.4
Average	6.2	6.1	6.1	5.3	

Main irrigation effect:	1.3***
Main sowing date effect:	1.0**
Main seeding rate effect:	n.s
I X D interaction:	*
I X R interaction:	n.s
D X R interaction:	n.s
I X D X R interaction:	n.s

TSW (g)

Rainfed:

	Sowing date:				
	SD1	*SD2*	*SD3*	*SD4*	Average
SR1	6	5.7	5.4	5	5.5
SR2	5.9	5.9	5.5	5.2	5.6
SR3	6.1	5.9	5.5	5	5.6
Average	6	5.8	5.5	5.1	

Irrigated:

	Sowing date:				
	SD1	*SD2*	*SD3*	*SD4*	Average
SR1	5.9	5.9	5.7	5.3	5.7
SR2	5.7	5.7	5.6	5.2	5.6
SR3	6.1	5.7	5.5	5.1	5.6
Average	5.9	5.8	5.6	5.2	

Main irrigation effect:	n.s
Main sowing date effect:	0.4***
Main seeding rate effect:	n.s
I X D interaction:	n.s
I X R interaction:	n.s
D X R interaction:	n.s
I X D X R interaction:	n.s

Seed yield (g/m^2)

Rainfed:

	Sowing date:				
	SD1	*SD2*	*SD3*	*SD4*	Average
SR1	152	103	99	83	109
SR2	157	117	82	75	108
SR3	134	106	106	80	107
Average	148	109	96	79	

Irrigated:

	Sowing date:				
	SD1	*SD2*	*SD3*	*SD4*	Average
SR1	211	174	128	136	162
SR2	256	134	142	115	162
SR3	264	114	108	115	150
Average	244	141	126	122	

Main irrigation effect:	36***
Main sowing date effect:	56***
Main seeding rate effect:	n.s
I X D interaction:	*
I X R interaction:	n.s
D X R interaction:	n.s
I X D X R interaction:	n.s

Plant density:

In the SD3 and SD4 treatments, plant density was significantly smaller under irrigation than under rainfed conditions. Furthermore, the proportional increase in plant density at final harvest across the three seeding rate treatments was less than at establishment. These responses are suggestive of self thinning due to greater biomass production under these conditions, as described previously for hemp (Chapter II.3). However, sequential harvest counts from the flax seeding rate trial discussed in Chapter III.2 did not indicate a significant decline in plant density with time for densities as high as 120 kg/ha.

Stem yield & dimensions:

Irrigation response.

All rainfed treatments showed some degree of water stress, ranging in severity from wilting to chlorosis and plant death in the more badly affected areas. More generally, development and senescence were promoted and stem elongation and thickening were stunted under rainfed conditions. The stem yields under irrigation were significantly greater than those under rainfed conditions across the three seeding rates and for SD2, SD3 and SD4. Even in the first sowing, which would have made the most of what water was available, there was a consistent though insignificant increase in stem yield with irrigation.

Sowing date response.

Stem yield was maximum for SD1 and tended to decline with progressively later sowings under both irrigated and rainfed conditions. The decline in stem yield was largest between SD1 and SD2; 230 g/m^2 for the irrigated treatments and 360 g/m^2 for the rainfed treatments. The absence of significant differences across the final three sowings is surprising. Of particular note is the relatively low stem yields for SD2. This may have been due to lodging and/or a possible reduction in plant density due to unfavourable conditions shortly after emergence. The greater severity of lodging observed in SD2, suggests that plants may have been at a growth stage more vulnerable to lodging during rainfall and irrigation events. Post emergence losses may have resulted from frost events in July and August. Data collected from the Hobart Airport indicated eleven frost days in July and a further 6 in August.

Stem length tended to decline with delay in sowing date for the rainfed treatments, although this decline was only significant between the first two sowings. The absence of a similar trend across the irrigated sowings may be attributed to the effects of lodging, which were more severe for the earlier sowings. Stem diameters for SD1 and SD2 were greater than for SD3 and SD4 under rainfed conditions. Under irrigation, stem diameter was maximum for the first sowing.

The percentage of bark in the stem was significantly higher for SD1 and SD2 compared with later sowings.

Seeding rate response.
For the first three sowing dates, SR2 and SR3 yielded more stem than SR1. Stem diameter generally declined with increasing seeding rate. The stem length for SR2 was greater than for SR3. There was some suggestion of a decline in stem yield between SR2 and SR3. Both lodging and self thinning may account for this response. Seeding rate effects are discussed in more detail in Chapter III.3.

Seed yield & seed yield components:
Capsule number per plant:
For SR1 and SD1, plant capsule number was much larger under irrigation than under rainfed conditions.

Under irrigated conditions and across the three seeding rates, capsule number tended to decline with sowing date delay.

A similar decline was apparent with seeding rate increase across the combinations of irrigation/rainfed and sowing date treatments.

Seed per capsule:
For SD1, SD2 and SD4, seed number per capsule was significantly higher under rainfed compared with irrigated conditions, presumably a compensatory response to the very large number of capsules set in the irrigated plots.

Across the rainfed plots, seed number per capsule was greater for SD1 and SD2 compared with later sowings.

Thousand seed weight:
There were no main effects for irrigation or seeding rate with this parameter.

Thousand seed weight was higher for SD 1 than for SD3 and SD4. Similarly, the TSW of SD2 was greater than for SD4.

Seed yield:
Main effects were significant for irrigation and sowing date treatments. Irrigated treatments generally yielded more seed than rainfed treatments, although significant differences were only apparent for SD1 and SD4. Similarly, seed yield tended to decline with sowing date delay, as expected from the above declines in component parameters. As with stem yield, seed yield declined sharply between the first two sowing dates. Across the rainfed plots, the seed yield for SD1 was greater than that for SD4. Across the irrigated plots, SD1 yielded more than for SD2, SD3 and SD4.

Flowering:
As for trial 1, flowering was delayed by progressively later sowings, with the delay in flowering time approximately half that of the delay in sowing time (Table III.3.5). The larger time intervals between sowing dates are reflected in the greater spread in calendar days and thermal time durations from sowing to flowering. The decline in thermal time durations with sowing date delay in this trial, coupled with the slight decline between the final two sowings at Forthside, suggests a daylength effect on flowering. Flax is a long day plant (Major 1980) and hence it would be expected that flowering of the later sown treatments would be accelerated by the lengthening days.

There was no apparent effect of seeding rate on flowering time. Rainfed treatments did however appear to flower before irrigated treatments. In the case of SD3, the difference was approximately 2 days, whereas for SD4 the difference was approximately 5 days.

Table III.3.5: Date of flowering, calendar days and thermal time (above a base temperature of 1 °C) from sowing to flowering for cv. Ariane in trial 2.

Trial 2: Cambridge 1996-97:

	Date:	Calendar Days:	Thermal time:
SD1	17.10.96	154	1345
SD2	26.10.96	123	1111
SD3	19.11.96	97	998
SD4	1.12.96	75	866

III.3.4 Discussion:

The results from the 1996-97 trial at Cambridge indicate that autumn sowings of flax offer potentially higher yields of both straw and seed compared with winter and spring sowings. These results for straw yield support the earlier reports of Tilt (1941), Wilson (1944) and Hansen (1945). All sowings benefited from irrigation between early November and January when the amount and distribution of rainfall was poor. This period coincides with flowering and early seed development when the plants are most vulnerable to water stress (Green *et al.* 1994, Turner 1987). The yield gains from irrigation were least for the autumn sowing, presumably due to earlier flowering and maturity.

Based on the results of the Cambridge trial, reasonable straw and seed yields are possible from dryland cropping of flax. Optimum results clearly depend on autumn sowing, good rainfall during winter and spring and/or cropping on moisture retentive soils. Rainfall during the 1996-97 season at Cambridge was substantially below average in the months of May, July, August and December. Other monthly figures were close to average (Figure III.3.1). The higher rainfall (see Figure II.4.1) conditions and more moisture retentive clay soils of the north west coast are likely to provide better results from autumn sown, rainfed cropping.

Stem yields from irrigated, spring sown crops at Forthside and Cambridge were still high, at between 600 and 1000 g/m^2. The potential for both winter and summer cropping of flax offers the potential to spread crop maturity and harvest times over a

wider time period. This would reduce some of the time restrictions associated with processing the crop and may also reduce storage costs.

Damage from frost at flowering (Green *et al.* 1994) is likely to be of little concern in the main agricultural areas of Tasmania, given that flowering occurs from mid to late October onwards when frost frequency and severity is low. Similarly, frost damage around emergence is also unlikely given the ability of this species to tolerate short periods of exposure down to temperatures as low as -6 °C (Green *et al.* 1994). Such temperatures are extremely rare in the main agricultural areas of Tasmania. Of potentially greater concern is damage from high temperatures at flowering (Green *et al.* 1994), especially in the case of spring sowings. Such damage was noted in the cultivar trials conducted at Cambridge, as reported in Chapter III.1.

Waterlogging effects (Elliott 1959) were not apparent in either trial. Problems might have been expected on the shallow, sandy loam over clay soil at Cambridge. Waterlogging effects were previously identified at an adjacent site in autumn sowings of hemp, a species prone to waterlogging.

The selection of an optimum seeding rate will depend on the sowing date and involve a compromise between maximising yield and minimising potential losses from lodging (Chapter III.2). The first two sowings in trial 2 were free of lodging at 80 kg/ha (~900 plants/m^2). An increase in seeding rate to 110 kg/ha (~1200 plants/m^2) resulted in higher stem yields, but was accompanied by a higher incidence of lodging. The decreased occurrence of lodging in the late winter (August 14) and early spring (September 17) sowings in the same trial suggests that later sowings can accommodate higher seeding rates. However, there was no evidence to suggest gains in stem yield at seeding rates above 110 kg/ha. In the seeding rate trial reported in the previous chapter (sown on September 26), stem yield generally increased (but not significantly) with seeding rate, but lodging was apparent at the highest two seeding rates of 120 kg/ha (~1930 plants/m^2) and 90 kg/ha (1344 plants/m^2).

Section IV: Development of a hemp simulation model.

IV.1 The effect of temperature on hemp seed germination, and elongation of the radicle and hypocotyl.

IV.1.1 Introduction:

In the absence of other limiting environmental factors such as soil moisture, soil compaction and the activities of soil fauna, temperature is the primary factor governing the duration from sowing to emergence (Garcia-Huidobro *et al.* 1982). The purpose of this study was to investigate the response of pre-emergent development of hemp to temperature. The primary objectives were to obtain estimates for the cardinal temperatures of hemp and to establish a simple model for predicting the duration from sowing to emergence; important elements of the hemp simulation model described in Chapter IV.4.

Previous references to the effect of temperature on pre- and post-emergent growth and development of hemp are scant. Tamm (1933) reported a sowing to emergence duration of 96 °Cd above a base temperature of 0 °C. Haberlandt (1897, cited by van der Werf *et al.* 1995) reported minimum, optimum and maximum cardinal temperatures for hemp seed germination of 1-2 °C, 35 °C and 45 °C respectively. More recently, van der Werf *et al.* (1995) investigated the effect of temperature on leaf growth and development in field trials with hemp. The base temperature for growth was found to be significantly larger than that for development; 2.5 °C and 1 °C respectively. From this same study, thermal time accumulations from sowing to 50% emergence ranged from 68 °Cd to 109.5 °Cd (above 0 °C base temperature), with an average of 88.3 °Cd. Base temperatures of 0 °C and 1 °C gave the smallest coefficients of variation for the calculation of pre-emergent thermal time.

For crops such as maize (Warrington & Kanemasu 1983) and pearl millet (Ong & Monteith 1985), post-emergent cardinal temperatures have been found to be relatively similar to those observed for pre-emergent development. A similar assumption is made in the development of the hemp model described later, with the cardinal temperatures reported in this study utilised for both pre- and post-

emergent growth and development.

Models have been developed for kenaf (Carberry & Abrecht 1990), pearl millet (Carberry & Campbell 1989), maize (Jones & Kiniry 1986) and sorghum (Maas & Arkin 1978) which assume that, providing the environmental influences other than temperature are non limiting, the duration of pre-emergence can be predicted from temperature response functions for three distinct phases. The first phase is from sowing to germination. Following germination, the elongation of the radicle and hypocotyl follow a sigmoidal pattern with time, beginning with a lag phase and then entering into a linear phase. Emergence occurs when the hypocotyl length equals the sowing depth. Estimates of cardinal temperatures for pre-emergent development can be made from plots of development rate versus temperature. A similar approach is adopted for hemp in this study.

IV.1.2 Materials and method:

Germination:

The germination response of the hemp cultivar Kompolti was measured at 13 different temperatures in incubators set at 1, 4, 10, 15, 20, 25, 30, 33, 37, 40, 45, 50 and 55 °C. For each temperature treatment, lots of 40 seeds were placed in four separate petri dishes lined with 3 sheets of Whatman No. 1 filter paper. The filter paper was moistened with a solution of 2 mmol/L $CaCl_2$ to facilitate imbibition.
The trial was commenced as soon as the seed was exposed to the moist filter paper. A seed was deemed to have germinated when at least 1mm of radicle was visible.

The number of germinants was measured at frequent and regular intervals determined by the rate of germination. For example, counts were taken on the hour for the 55 °C treatment and every five days for the 1 °C treatment.

Temperature measurements were taken at the time of each count to monitor treatment variability. Average treatment temperatures for the duration of the trial are shown in Table IV.1.1.

Table IV.1.1: Average incubator temperatures for each germination treatment.

Treatment (°C)	Average Temp.(°C)	Standard deviation
1	1.2	0.3
4	4.1	0.1
10	10.0	1.3
15	14.9	0.7
20	20.5	0.1
25	25.2	1.0
30	29.6	0.5
33	32.5	0.3
37	37.0	1.5
40	40.0	0.2
45	45.3	0.2
50	50.3	0.9
55	54.3	2.2

Elongation of hypocotyl and radicle:

The response of radicle and hypocotyl elongation to temperature was measured at 8 different temperatures in incubators set at 10, 15, 20, 25, 30, 33, 37 and 40 °C. The method used was based on approaches described by Burris and Fehr (1971), Hatfield and Egli (1974), and Carberry and Abrecht (1990).

Firstly, two sheets of 0.25 mm thick blotting paper were cut to size; 30 cm wide X 23 cm long. One of the sheets was laid on a flat surface and moistened with a solution of 2 mmol/L $CaCl_2$. Ten representative germinants were taken from the corresponding temperature treatments of the above germination trial and positioned along a line 7 cm down from the top of the sheet, orientated with radicle pointing to the base of the sheet. The second sheet was placed over the first and moistened so as to firm the seeds into place. The sheets were then rolled together to form a cylinder (~5 cm in diameter) with the seeds arranged in a ring at one end. The cylinder was then placed upright (seeds to the top) in a 100 ml beaker containing 60 ml of 2 mmol/L $CaCl_2$. The blotting paper effectively acted as a wick, maintaining a moist environment around the seedlings. The whole apparatus was then surrounded by a sealed plastic bag to prevent the paper from drying out. Four replicate cylinders were prepared for each treatment.

Regular and frequent measures of radicle and hypocotyl length were made in order to prepare temperature response functions for elongation. The cylinder was

unrolled and the seedlings exposed by pulling back the top sheet of paper. The transition from hypocotyl to radicle was identified by an area of hypocotyl thickening and/or the presence of root hairs on the radicle. Once identified, this transition was marked with a soft pen. The total length was measured from the tip of the radicle to the highest point of the seedling, initially taken as the base of the seed testa and later, as the apex of the hypocotyl hook. The length of the radicle was also measured and subtracted from the total length to give the hypocotyl length (Carberry & Abrecht 1990).

As with the germination trial, incubator temperatures were recorded throughout the duration of the trial (Table IV.1.2). The trial continued until each seedling had emerged from the top of the cylinder or, in the case of the higher temperature treatments, when elongation ceased.

Table IV.1.2: Average incubator temperatures for the elongation treatments.

Treatment (°C)	Average Temp.(°C)	Standard deviation
10	9.8	1.3
15	15.2	0.8
20	20.4	0.2
22.5	23.2	0.8
25	25.9	1.4
27.5	27.3	0.5
30	29.5	0.9
33	33.1	0.3
37	36.3	1.7

Data analysis:

The maximum germination percentage for each temperature treatment was calculated as the average of the four replicates. The rate of germination (1/hr) was taken as the reciprocal of the time at which 50% of this maximum germinant number was reached (denoted by G50), as determined by interpolation.

A logistic equation of the form:

$$Y=Ymax/(1+exp(-k(X-m))),$$

where Ymax represents the asymptote and m represents the time at which maximum elongation rate occurs (Carberry & Abrecht 1990), was fitted to each radicle and hypocotyl elongation response using non-linear regression techniques.

The rate of elongation (mm/hr) during the phase of linear increase was taken as the slope of the response between 75% and 25% of Ymax. Adopting a similar approach to Carberry and Abrecht (1990), the duration of the lag phase was taken as the duration from G50 to the time when the radicle was 1 mm and the hypocotyl was 0 mm (determined by extrapolation from the linear rates of elongation). The reciprocal of this duration gave the rate of development (1/hr) for the lag phase.

The thermal time duration of the three phases was then determined from plots of rate versus temperature. Where the rate (1/t) of each phase increased linearly with temperature between a base temperature (Tb) and an optimum temperature (To), then:

$1/t = (T-Tb) / Z_1$, for $Tb<T<To$ (1).

Similarly, where the rate decreased linearly beyond To to a maximum temperature (Tm), then:

$1/t = (Tm-T) / Z_2$, for $To<T<Tm$ (2).

Z_1 and Z_2 represent the thermal time duration, or the inverse of the slope of the rate versus temperature plot. Extrapolations of equations (1) and (2) to the X axis provided estimates of the base and maximum temperatures respectively. Equating the two equations provided an estimate of the optimum temperature. By multiplying (Tm-T) in equation (2) by Z_1/ Z_2, the system can be treated as though the thermal time duration is Z_1 both below and above To. Since Z_1/ Z_2 can be expressed as (To-Tb)/(Tm-To), equation (2) becomes $1/t=[(T0-Tb)(Tm-T)/(Tm-To)]/Z_1$ (3) (Garcia-Huidobro *et al.* 1982).

This double linear description is an approximation to a curvelinear response. It has been reported for kenaf (Carberry & Abrecht 1990) and a number of other crops (Angus *et al.* 1981), that there were no significant gains in the prediction of emergence from using non linear or curvelinear models in place of the linear approach. Furthermore, the linear model is preferred because of its simplicity and wide application (Carberry & Abrecht 1990). For the purposes of comparison, a non-linear equation developed by Reed *et al.* (1976) and proposed by Landsburg (1977) as a useful equation for describing temperature response:

$1/t=a(T-Tb)(Tm-T)^b$,

where $a=Ymax/[(To-Tb)(Tm-To)^b]$, $b=(Tm-To)(To-Tb)$ and Ymax is the maximum

rate, was also fitted to the temperature responses.

All regression analyses were performed using Systat 5.2.1 software.

IV.1.3 Results:

Germination:

At 10 °C, the first germinants were apparent after 18 hours, with the maximum number (34) reached after 9 days. At 40 °C, the first sign of germination appeared before 9 hours, with the maximum number of germinants (18) after 19 hours (Figure IV.1.1). The plots for 4 °C and 1 °C are not shown. Approximate times for the appearance of the first and maximum number of germinants at 4 °C, were 85 hours and 240 hours respectively.

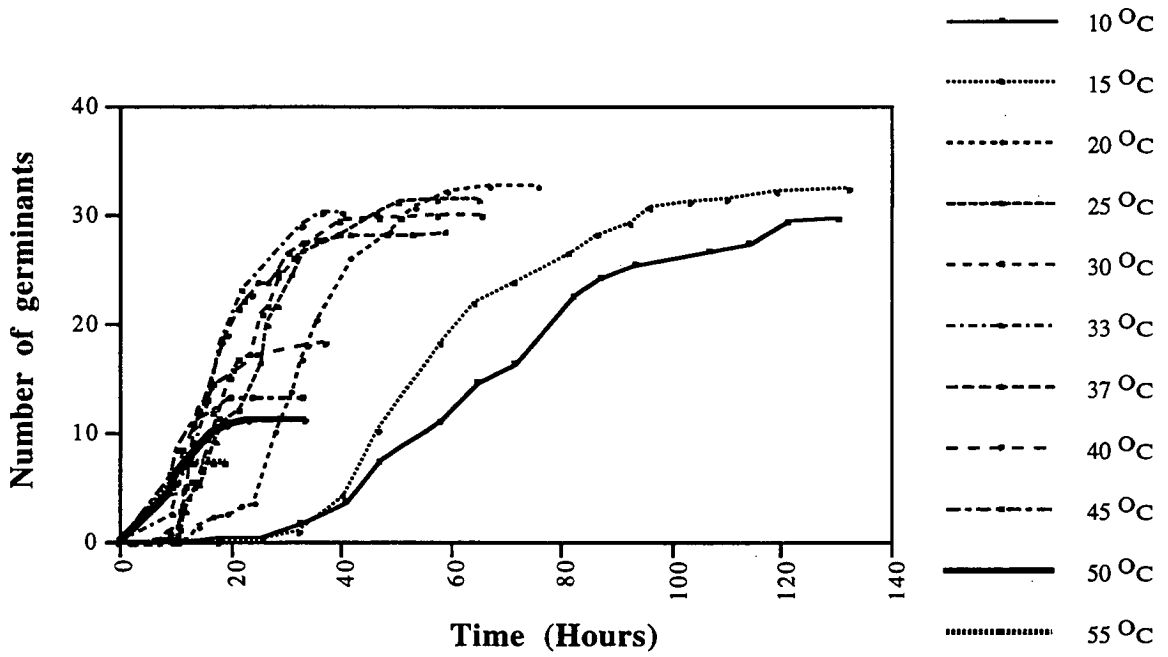


Figure IV.1.1: Time response plots for germinant number for 10 separate temperature treatments.

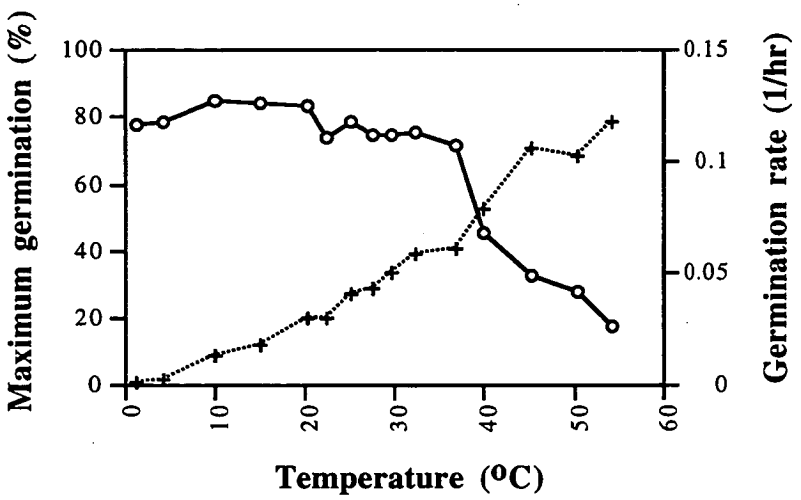


Figure IV.1.2: Temperature response plots for the maximum number of germinants (o) and the rate of germination (+).

The maximum germination percentage remained relatively constant at 78.8% (SD 4.1%) from approximately 1 to 33 °C, and then declined to be 18% at 54 °C (Figure IV.1.2).

Within the temperature range of this trial, the rate of germination (1/G50) increased across all treatments (Figure IV.1.2). A good fit was achieved with a linear model ($Y=0.0023X-0.012$, $R^2=0.96^{***}$), which gives a thermal time duration for germination of 18.4 °Cd above a base temperature of 5.4 °C.

Elongation of hypocotyl and radicle:

The sigmoidal patterns of elongation of the radicle and hypocotyl with time after G50 are shown in Figures IV.1.3a and IV.1.3b respectively. No elongation was apparent for the 40 °C treatment. Coefficients for the fitted logistic equations are shown in Table IV.1.2.

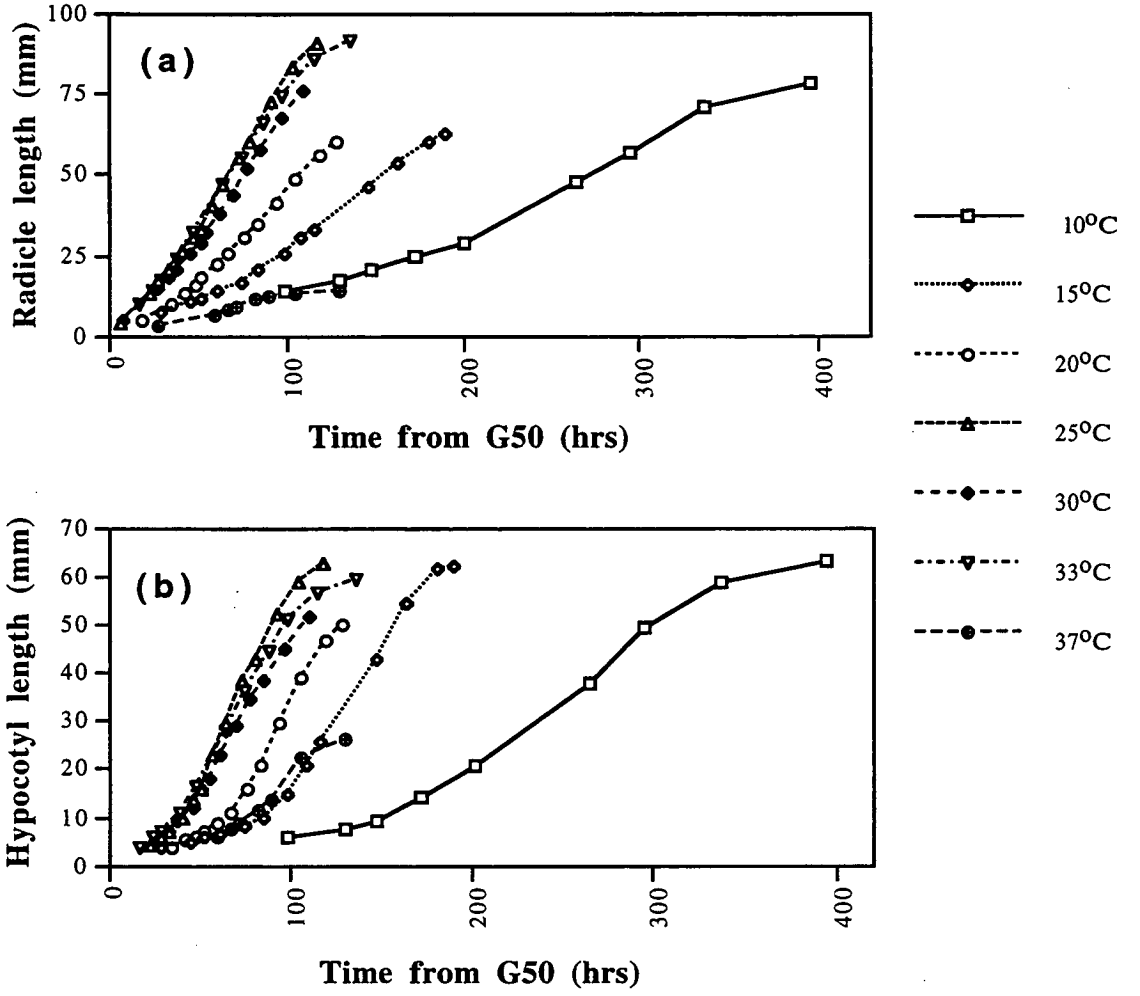


Figure IV.1.3: Time response plots for hypocotyl (a) and radicle (b) elongation.

Rates of development for the lag phase and elongation of the linear phase are plotted against temperature in Figures IV.1.4 and IV.1.5, respectively. Piecewise linear regressions fitted to these plots were based on four data points below and four above the apparent optimum temperature (Table IV.1.3). Cardinal temperature estimates derived from these equations are listed in Table IV.1.4.

Table IV.1.2: Fitted coefficients (+/-SE) for the logistic equation, Y=Ymax(1+exp(-k(X-m)) fitted to time response plots for radicle and hypocotyl elongation (Figure IV.1.3).

Temp. (°C)	Ymax (mm)	k (h)	m	R^2
Radicle:				
10	97.4 (5.6)	0.011 (0.001)	264.4 (12.3)	0.99
15	80.1 (1.9)	0.022 (0.001)	136.0 (2.7)	0.99
20	76.0 (2.4)	0.033 (0.001)	79.9 (2.3)	0.99
25	105.1 (3.5)	0.039 (0.002)	69.4 (2.2)	0.99
30	94.6 (3.3)	0.037 (0.001)	71.0 (2.3)	0.99
33	97.0 (1.9)	0.039 (0.001)	66.9 (1.5)	0.99
37	15.1 (0.7)	0.052 (0.007)	56.4 (2.6)	0.97
Hypocotyl:				
10	68.7 (2.1)	0.018 (0.001)	246.9 (5.4)	0.99
15	74.7 (3.2)	0.033 (0.002)	126.6 (3.6)	0.99
20	61.5 (2.4)	0.049 (0.002)	88.0 (2.1)	0.99
25	65.7 (1.1)	0.060 (0.002)	67.4 (0.8)	0.99
30	57.6 (1.3)	0.051 (0.002)	68.6 (1.2)	0.99
33	61.3 (0.6)	0.052 (0.001)	67.3 (0.6)	0.99
37	31.3 (2.9)	0.049 (0.007)	85.0 (5.0)	0.98

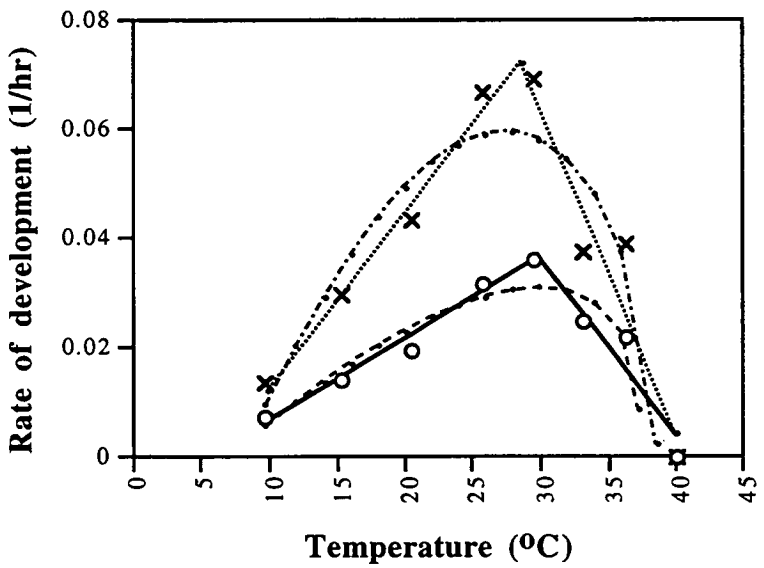


Figure IV.1.4: Temperature response plots for the rate of development for the lag phase of radicle (x) and hypocotyl (o) elongation. Piecewise linear regressions for radicle (....) and hypocotyl (–). Non-linear regressions for radicle (·---) and hypocotyl (- - -).

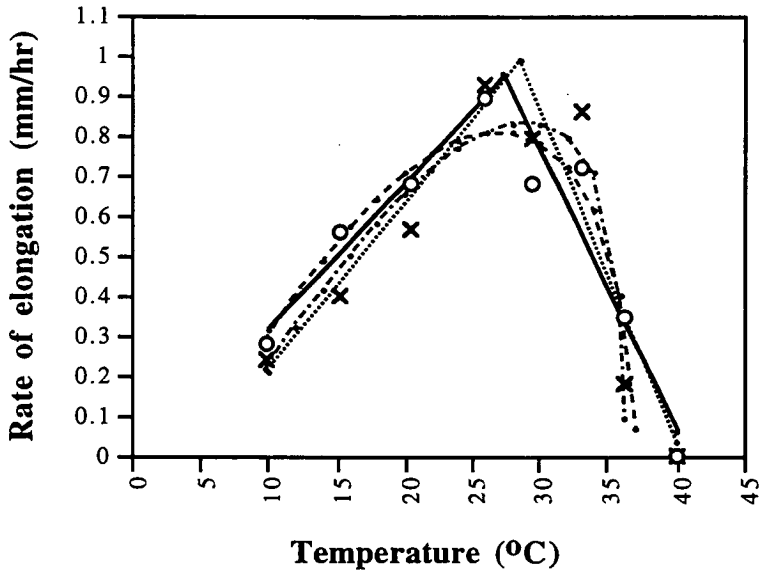


Figure IV.1.5: Temperature response plots for the rate of elongation during the linear phase of elongation for the radicle (x) and hypocotyl (o). Piecewise linear regressions for radicle (····) and hypocotyl (–). Non-linear regressions for radicle (·-·-) and hypocotyl (- - -).

Table IV.1.3: Fitted linear regression coefficients for the rate vs temperature plots for the lag and linear phases of radicle and hypocotyl elongation;
$1/t = (T-Tb) / Z_1$ ($Tb<T<To$) and $1/t = (Tm-T) / Z_2$ ($To<T<Tm$). The significance of the linear models is identified by the asterisks ($P<0.05$ *; $P<0.01$**, $P<0.001$***).

Lag phase:				
	Radicle:		Hypocotyl:	
	Tb->To	To->Tm	Tb->To	To->Tm
Intercept	-0.0198	0.244	-0.0079	0.132
Slope	0.0032	-0.006	0.0015	-0.0032
R^2	0.98*	0.90*	0.97*	0.92*
Linear phase:				
	Radicle:		Hypocotyl:	
	Tb->To	To->Tm	Tb->To	To->Tm
Intercept	-0.209	3.509	-0.0522	2.862
Slope	0.0419	-0.088	0.0369	-0.07
R^2	0.95*	0.82 (P=0.093)	0.98**	0.86 (P=0.074)

Table IV.1.4: Estimates for the base, optimum and maximum cardinal temperatures (°C) for the lag and linear phases of radicle and hypocotyl elongation based on piecewise linear regression.

	Lag phase:		Linear phase:	
	Radicle	Hypocotyl	Radicle	Hypocotyl
Tb	6.2	5.3	5	1.4
To	28.7	29.8	28.6	27.3
Tm	40.7	41.3	39.9	40.9

In both the lag and linear phases of elongation, the rate of development was faster for the radicle than for the hypocotyl, especially during the lag phase.

Estimates of optimum and maximum temperature did not vary greatly between the radicle and hypocotyl and across the two phases of elongation. The optimum temperature ranged from 27.3 °C to 28.6 °C and the maximum temperature from 38.8 °C to 40.9 °C. In contrast, the range of base temperature estimates varied considerably from 1.4 °C to 6.2 °C.

Elongation of the hypocotyl required 27.7 °Cd above a base temperature of 5.3 °C for the lag phase and 1.13 °Cd/mm above a base temperature of 1.4 °C for the linear phase.

The non-linear model equation of Reed *et al.* (1976) also provided a good fit to the rate response data, as evidenced by low residual mean square values. Base temperature estimates were generally higher and maximum temperatures lower than for the linear model. Optimum temperatures tended to be similar (Table IV.1.5).

Table IV.1.5: Estimates for the base, optimum and maximum cardinal temperatures (°C) for the lag and linear phases of radicle and hypocotyl elongation based on the non-linear equation of Reed *et al.* (1976).

	Lag phase:		Linear phase:	
	Radicle	Hypocotyl	Radicle	Hypocotyl
Tb	7.9	7.1	5.8	4.8
To	27.5	29.9	29.0	26.9
Tm	38.6	37.4	36.3	37.0

IV.1.4 Discussion:

The observed decline in maximum germinant number at high temperatures was not reflected in a decline in the rate of germination, as previously observed for other crops such as kenaf (Carberry & Abrecht 1990) and pearl millet (Garcia Huidobro *et al.* 1982). This measure of rate appears unsatisfactory for obtaining estimates for the optimum and maximum cardinal temperatures as it does not take into account the decline in germinant number at high temperatures. The temperature at which the number of germinants begins to decline is close to the optimum temperature predicted from the elongation response. Based on a fitted linear model to the data points up to this assumed optimum temperature of approximately 30 °C, the base temperature and thermal time duration for germination were 1.9 °C and 24.5 °C.d respectively.

Given that the relation between germination rate and temperature appears sigmoidal, the base temperature estimate is sensitive to the range of temperatures over which the linear model is fitted. Over a low range of temperatures about the tail of the rate response, a slower duration and lower base temperature can be expected from the linear approximation (Angus *et al.* 1991). This has previously been observed in hemp by van der Werf *et al.* (1995). They found that the base temperature estimates from field trials, where the plants were exposed more to lower temperatures, was less than that observed in the glasshouse under a higher temperature regime.

Both the non-linear and piecewise linear models provided reasonable fits to the

elongation rate data. On the basis of its simplicity and wide application (Carberry & Abrecht 1990), the linear model was subsequently used for the prediction of emergence.

With the exception of the hypocotyl linear elongation result, base temperature estimates from the elongation study were generally high relative to reported values for hemp (0-2.5 °C). As for the germination response, the elongation rate response to temperature appeared sigmoidal below the optimum temperature. Consequently, the linear models fitted to this response will tend to overpredict the base temperature.

Based on the linear model developed in this study and assuming that the optimum temperature for germination is equivalent to that for elongation, the thermal time requirements for germination and the lag phase of hypocotyl elongation were 24.5 °Cd and 27.7 °Cd respectively. The duration of the linear phase of elongation was 1.13 °Cd/mm. Thus, from a depth of 30 mm it will take 86.1 °Cd for 50% emergence. This prediction is close to reported values and to observations made of emergence during the glasshouse trial described in the following chapter. In this trial, seeds were sown into potting mix at a uniform depth of 30 mm and regular observations made up until 50% emergence. Thermal time durations for pre-emergence were calculated from the area under thermograph plots taken from the glasshouse. The durations for the two glasshouse trials were 81.2 °Cd and 91.3 °Cd above a base temperature of 1 °C.

The considerable difference between the base temperature estimates for the two phases of hypocotyl elongation has previously been observed for kenaf (Carberry & Abrecht 1990). In selecting a base temperature for use in a simulation model for kenaf (Carberry *et al.* 1992), preference was given to values derived from the hypocotyl linear elongation and germination phases. This centred on the fact that the rate response plots for the latter two phases are based on actual observations (P. Carberry, pers. comm. 1997). Furthermore, by assuming that the linear and germination phase base temperature applied for the lag phase, the effect on the predicted duration from sowing to emergence was deemed to be insignificant (Carberry & Abrecht 1990).

Selection of a common base temperature for use in the crop simulation model (Chapter IV.4) was difficult, given the large variability in estimates from this study. Taking into consideration the sigmoidal nature of the rate responses and the high level of germination observed at 1 °C, it is likely that the base temperatures for germination and elongation falls within the range of previously reported values. Consequently, a value of 1 °C was selected for use in predicting the pre-and post-emergent growth and development of hemp.

Optimum and maximum cardinal temperatures for elongation were taken as the average of values estimated from the linear model for elongation, ie 28.3 °C and 40.1 °C respectively.

Assuming a common base temperature of 1 °C, the average thermal time requirements for germination and the lag and linear phases of hypocotyl elongation become 24.1 °Cd, 44.5 °Cd and 1.34 °Cd/mm respectively. This amounts to approximately a 1.5 day increase in the duration to emergence. This difference is within the expected error margin for phenology prediction in crop models.

IV.2 The flowering response of two hemp cultivars to photoperiod.

IV.2.1 Introduction:

The duration from sowing to flowering is an important determinant of fibre yield potential in hemp, since maximum stem yield occurs shortly after flowering (Meijer *et al.* 1995). As a short day plant, daylength has a key influence on the timing of flowering in hemp (Heslop Harrison & Heslop-Harrison 1969). The purpose of this study was to investigate the flowering response to photoperiod of two selected hemp cultivars that have performed well in Tasmania field trials (Section II). The key parameters describing this response are required to simulate post-emergent phenology in the hemp crop model described in Chapter IV.4.

The approach used here to describe the response to photoperiod is based on a scheme developed by Major (1980). The vegetative phase of growth from emergence to floral initiation is broken down into a temperature dependent juvenile phase and a daylength dependent photoperiod induced phase (PIP). Under optimum daylength conditions, the duration of the PIP is a constant, minimum number of days. The sum of this minimum PIP and the juvenile phase is referred to as the basic vegetative phase (BVP). In the case of short day plants such as hemp, longer daylengths increase the length of the PIP. The longest daylength that does not have a delaying effect on the floral initiation is referred to as the maximum optimal photoperiod (MOP). Nonoptimal daylengths increase the duration of the PIP in proportion to the genetically controlled photoperiod sensitivity (PS), expressed in units of thermal time (^{o}Cd) delay per hour of increase in daylength. This can be measured from the slope of the thermal time response curve above the MOP. The photoperiod above which floral initiation either does not take place or occurs in the same number of days regardless of daylength, is the critical photoperiod (CP). The duration from floral initiation to flower formation is referred to as the flower development phase (FDP).

The first evidence of a shift from vegetative growth to flowering in hemp is identified by the formation of undifferentiated primordia in the axils of the stipules, just adjacent to the axillary buds (Heslop-Harrison & Heslop-Harrison 1969). In experiments with Chilean and Kentucky varieties, Borthwick and Scully (1954)

observed that flowering occurred promptly in daylengths of 14 or fewer hours and with considerable delay, or not at all in daylengths above 16 hours. Heslop Harrison & Heslop-Harrison (1972), report a maximum optimal photoperiod of just 9 hours for a Portuguese fibre variety from Coimbra and a small seeded drug cultivar from India. The same authors report that the critical photoperiod lies somewhere between 20 and 24 hours. Similarly, van der Werf *et al.* (1994) reported that substantial numbers of Fedrina 74 and Kompolti Hybrid TC plants eventually flowered even under continuous (24 hour) illumination.

Consequently, in respect to primordium formation, all hemp varieties are generally viewed as quantitative short day plants. The response to photoperiod from initiation to flowering is somewhat more ambiguous, with varieties varying in their response from obligate to quantitative. In those varieties with an absolute requirement for short days, the primordia either fail to develop or are shed under long days (Heslop Harrison & Heslop-Harrison 1969).

Major *et al.* (1991), report that the description of daylength in units of thermal time may eliminate much of the influence of a temperature by daylength interaction on the timing of flowering. This has previously been observed for soybean (Hadley *et al.* 1984) and sorghum (Major *et al.* 1990), except at extremely high temperatures. Similar findings have been reported for hemp by Nelson (1944). In an experiment with a variety from Portugal at a continuously inductive photoperiod of 8 hours, initiation occurred after 24.5 days at a constant temperature of 15.5 °C; after 19 days at 22 °C; and after 18 days at 26 °C. Thermal time duration varied little between the lower two temperatures (355 and 378 °Cd above 1 °C respectively) but increased dramatically under the highest temperature regime (450 °Cd above 1 °C). For the purposes of the hemp simulation model, it is assumed that the effect of temperature on the flowering response is accounted for by the use of thermal time as a measure of phenology. The validity of this approach would need to be further investigated with more extensive trials under varying temperature regimes.

IV.2.2 Materials & Method:

Growth chamber:

In the absence of a growth chamber large enough to accommodate mature hemp plants, a new controlled environment facility had to be constructed. A wooden

framed, masonite clad box measuring 2.5 m (height) X 2.3 m (width) X 4 m (length) was erected inside an existing glasshouse at the Horticultural Research Centre at the University of Tasmania (Figure IV.2.1). The box was divided into two light tight compartments referred to as the main and ante-chambers. The small ante-chamber (0.8 m in length) at the front end of the box enabled treatments to be moved into the main chamber (3.2 m in length) without the introduction of light from outside.

Access to and from the ante-chamber and between the ante and main chambers was through retractable curtains constructed from 300 μm thick black plastic. Plastic pelmets were constructed to prevent light coming in around the edges of each closed curtain.

Ventilation was achieved with an extractor fan mounted in the rear wall of the main chamber. A number of slots were cut in the walls of the box to allow for air entry. Black plastic housings were erected on the exterior of the box to prevent light entry through these ventilation features.

Thermographs were positioned in the main glasshouse and in the rear (mid height) of the main chamber to provide continuous measures of air temperature. The temperature regime in the glasshouse was maintained between a minimum of 15 ^{o}C and a maximum of 24 ^{o}C.

Photoperiod extension was achieved by rigging banks of six and three 100 W incandescent globes in the main and ante-chambers respectively. These lights were spaced horizontally so as to distribute a uniform intensity of light over the chamber area. The height of the lights was adjusted to provide a minimum light intensity of 5 E/m^2/sec at pot level, sufficient to inhibit flowering in hemp (Borthwick & Scully 1954). Each light bank was plugged into timer switches to facilitate automatic operation.

Experimental design and operation:

Two trials were conducted over a period from 17/9/96 to 17/1/97 to investigate the flowering response to photoperiod of the cultivars, Kompolti and Futura 77. Trial 1 included photoperiods of 8, 10, 12, 14 and 16 hours. Trial 2 investigated photoperiods of 10, 12, 14 and 15 hours.

Figure IV.2.1: (1) Growth chamber used in photoperiod response trial: vent (a), extractor fan (b), main chamber (c), ante-chamber (d), light proof curtain + pelmet (e). (2) Different plant heights associated with the five photoperiod treatments: 8, 10, 12, 14 and 16 hours (L-R).

Each photoperiod treatment was set up on individual trolleys to facilitate movement in and out of the chambers. Each trolley held ten pots, five for each of the two cultivars.

Plants were established in 40 cm (height) X 40 cm (diameter) pots. The potting mix consisted of a 4:1 mix of composted pine bark and coarse washed river sand. To this were added 300 g/50L of Osmocote (slow release macronutrient mix: 16% N, 3.5% P, 10% K, 2.4% S, 1.2% Mg + assorted trace elements; B,Cu, Fe, Mn, Mo and Zn), 200 g/50L of dolomite, 25 g/50L of $FeSO_4$ and 20 g/50L of Micromax (micronutrient mix: 12% Fe, 2.5% Mn, 1% Zn, 0.5% Cu, 0.1% B, 0.005% Mo, 15% S). The plants were hand watered on a daily basis.

Pots were oversown to account for the low germination percentages of the two seedlots. After emergence, the plant population was hand thinned back to approximately 13 plants per pot.

During the period from sowing to approximately 50% emergence, the treatments were left outside the growth chamber in natural daylight. At the end of the day of emergence, all the trolleys were moved into the chamber (four in the main chamber and one in the ante-chamber) in order of increasing daylength treatment. The automatic lights were set to come on at 5.00am each morning so that all treatments commenced at the same time. At approximately 8:30am, all the trolleys were moved out into the natural daylight conditions of the glasshouse. At times governed by the photoperiod treatment, each trolley was subsequently returned to the growth chamber (ie the 8 hour treatment at 1pm, 10 hour treatment at 3pm, 12 hour treatment at 5pm, 14 hour treatment at 7pm and 16 hour treatment at 9pm). The light bank in the ante-chamber was used to extend natural daylength in the evening to meet the requirements of the 16 hour treatment.

Data collection and analysis:

After approximately three weeks, observations commenced for evidence of floral initiation. At first, this involved destructive sampling of a small number of plants removed from each cultivar by photoperiod combination and subsequent dissection under a microscope to look for primordia (Heslop Harrison & Heslop-Harrison 1969). Once primordia were observed, larger samples of 7 plants per

treatment per day were collected to more accurately determine the time of floral initiation and flowering. Initiation was deemed to have occurred when 50% or more of the harvested plants had one or more primordia visible. Similarly, flowering was reached when 50% or more of the plants had pedicillate male or stigmatic female flower structures. The remaining plants were maintained through until final harvest. This was taken as the time when 50% of the male (in the case of the dioecious cv. Kompolti) or monoecious plants (in the case of Futura 77) were shedding pollen.

Thermal time summations were measured by integrating the relevant portions of the glasshouse and growth chamber thermograph plots. This involved cutting out the profile of the graph above the selected base temperature (1 °C) and measuring the area under the graph with a planimeter.

A piecewise linear model was fitted to the photoperiod response using Systat 5.2.1 statistical software. The use of this linear model has been reported by Major (1980) to provide a better fit than a quadratic model.

IV.2.3 Results:

Table IV.2.1: Days and thermal time (day degrees above 1.0°C) from emergence to 50% floral initiation, 50% flowering and final harvest for trials 1 and 2.

Futura 77:

	Trial 1:		Trial 2:		
Hours	Initiation	Flowering	Initiation	Flowering	Harvest
8	22 (416)	27 (496)	-	-	-
10	21 (392)	25 (461)	22 (366)	27 (446)	39 (650)
12	20 (373)	24 (438)	22 (368)	26 (431)	37 (610)
14	21 (391)	25 (462)	24 (397)	28 (465)	37 (628)
15	-	-	36 (616)	41 (727)	50 (880)
16	50 (935)	55 (1019)	-	-	-

Kompolti:

	Trial 1:		Trial 2:		
Hours	Initiation	Flowering	Initiation	Flowering	Harvest
8	22 (405)	26 (487)	-	-	-
10	21 (398)	26 (491)	22 (366)	28 (463)	40 (684)
12	21 (397)	25 (469)	23 (383)	27 (449)	38 (650)
14	23 (443)	28 (527)	25 (414)	29 (484)	41 (703)
15	-	-	40 (691)	45 (766)	60 (1022)
16	49 (930)	54 (1013)	-	-	-

The durations from emergence to floral initation, flower formation and final harvest are shown in Table IV.2.1. Figures IV.2.2a and IV.2.2b are the thermal time response plots for Kompolti and Futura 77 respectively.

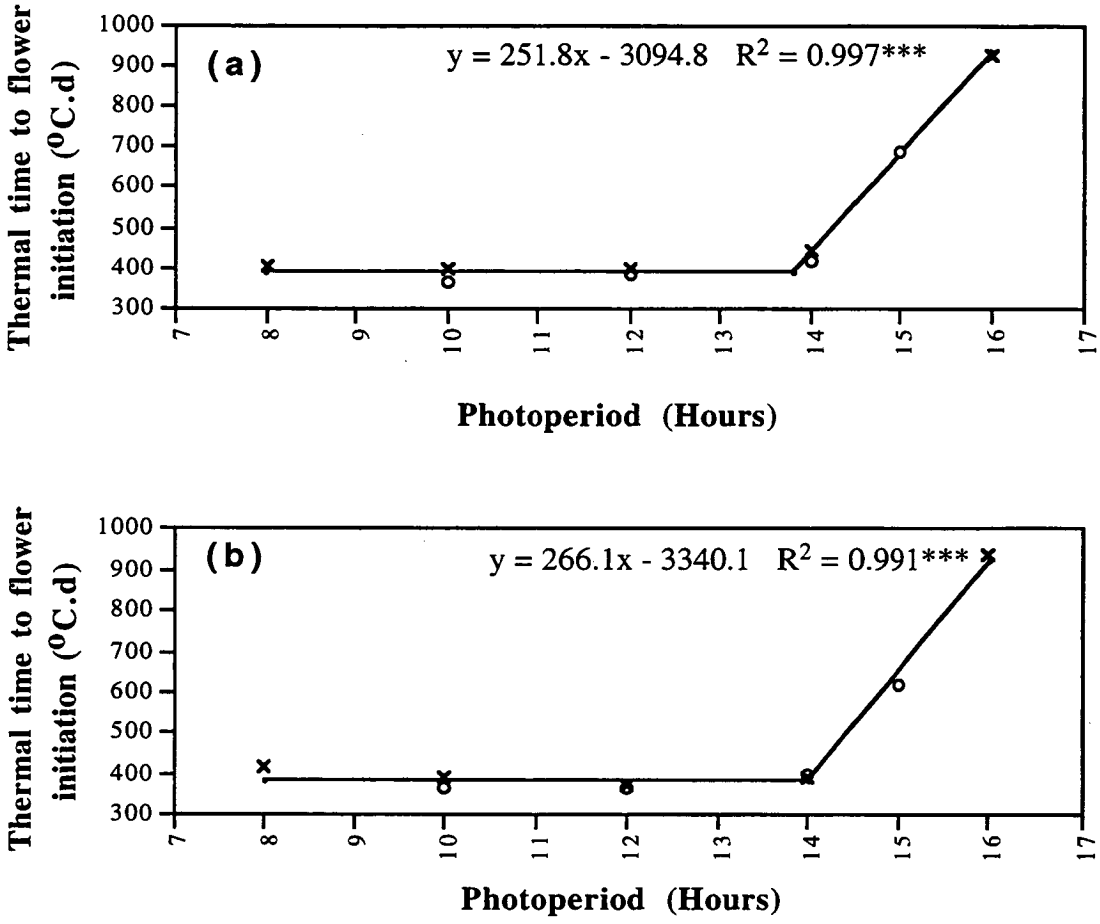


Figure IV.2.2: Photoperiod response plots for thermal time duration from emergence to floral initiation for Kompolti (a) and Futura 77 (b) in trials 1(x) and 2(o). Linear equations correspond to the photoperiod sensitive portion of each plot.

The estimates for the key phenology parameters defined by Major (1980) are shown in Table IV.2.2.

The photoperiod sensitivity was calculated from the slope of the linear regression model fitted through the data points corresponding to the 14, 15 and 16 hour photoperiods. These results indicate that Futura 77 is slightly more sensitive than Kompolti to photoperiods in excess of the maximum optimal photoperiod.

Basic vegetative period was taken as the average of the thermal time summations

for the 8, 10 and 12 hour treatments. The maximum optimal photoperiod corresponded to the intersection of this average value with the line fitted through the photoperiod sensitive region of the response. Estimates for these two parameters were similar for the two cultivars.

The duration of the flower development period and the period from flowering to harvest did not show any clear trend with photoperiod for either cultivar. Consequently, the durations of these phases were averaged across all the treatments. Cultivar differences for FDP were insignificant, whereas the duration from flowering to harvest was significantly greater for Kompolti (t-test, 5% probability).

Table IV.2.2: Estimates for key phenology parameters.

Parameter	Futura	Kompolti
Basic vegetative period (^{o}Cd)	383	390
Maximal optimum photoperiod (hr)	14	13.8
Photoperiod sensitivity (^{o}Cd/hr)	266.1	251.8
Flower development period (^{o}Cd)(SD)	76.8 (14.8)	80.2 (10.4)
Flower - harvest (^{o}Cd) (SD)	174.8 (22.5)	224.3 (23)

IV.2.4 Discussion:

The flowering responses to photoperiod for the two hemp cultivars, Kompolti and Futura 77 were typical for a short day plant. Flowering occurred rapidly in photoperiods less than approximately 14 hours and with increasing delay at higher photoperiods.

The estimates for basic vegetative period are close to the 399 ^{o}Cd (above 1 ^{o}C) reported for a variety from Portugal (Heslop Harrison & Heslop Harrison 1972). However, the maximum optimal photoperiod of 9 hours reported for the same variety is much less than that observed here for Kompolti and Futura 77. The approximate value of 14 hours reported by Borthwick and Scully (1954) for Chilean and Kentucky varieties, is in closer agreeance with these current results. The critical photoperiod is clearly greater than the maximum daylength simulated in this trial and hence the maximum daylength occurring in Australia.

The parameters determined in this study to describe the response of Kompolti to photoperiod were subsequently used in the development of the hemp model (Chapter IV.4) to simulate post emergent phenology. As part of the validation process, comparisons were made with observed thermal durations from sowing to flowering for 14 independent field sowings of Kompolti in Tasmania. The phenological model accounted for approximately 83% of the variation in observed flowering dates. While this is at the higher end of model prediction accuracy, the different responses between the two trial sites (Figure IV.4.6) suggest that other factors are influencing the flowering reponse. These might include plant nutrition, temperature (Heslop Harrison & Heslop Harrison 1969) and plant density (Chapter II.3 and van der Werf 1997).

IV.3 The effect of plant density on leaf appearance, expansion and senescence in hemp.

IV.3.1 Introduction:

The production of green leaf area is a key influence on light interception and hence the accumulation of plant biomass. In this chapter, data relating to leaf appearance, expansion and senescence collected from the plant density trial described in Chapter II.3, are used to develop predictive relationships for leaf area production in hemp. These relationships will be used in the development of the hemp simulation model described in Chapter IV.4.

Leaf appearance in hemp has previously been investigated by van der Werf *et al.* (1995). They observed that leaf pairs appeared at a regular rate determined from the slope of the straight line relationship between leaf pair appearance and thermal time. Similar linear relationships have also been observed for leaf pair senescence in hemp (H.M.G. van der Werf, unpublished data).

These simple relationships suggest the suitability of a modelling approach previously used for maize (Muchow & Carberry 1989, 1990), sorghum (Carberry *et al.* 1993) and kenaf (Carberry & Muchow 1992) in which leaf production is broken into the component processes of leaf appearance, leaf expansion and leaf senescence. Model equations and parameters were first developed for each process. The green leaf area was then predicted over time by coupling the rate of node (leaf) appearance with predicted leaf area per node and discounting for leaf area senescence. A similar approach is adopted here for hemp.

IV.3.2 Method:

Data pertaining to leaf area production were collected as part of the plant density trial conducted at the Forthside Research Station during the 1995/96 season. Cultural details of this trial are reported in Chapter II.3.

At fortnightly intervals, a sequential harvest of 0.5 m^2 was collected from each plot. Approximately 20 representative plants were then randomly selected for measurement of total and senesced node number and the area of fully expanded

leaves at each node. Supplementary *in situ* nodal counts were made at time intervals midway between the destructive sequential harvests. Nodes were deemed to be senesced when the nodal leaves were either shed or entirely yellow in color. The cotyledonary node was included as part of the count.

In hemp, phyllotaxis changes from opposite to alternate at or about the commencement of flowering. However, nodes still appear along the stem in distinct pairs. Consequently, for the purposes of the hemp model, paired nodes with alternate leaves were regarded as one node.

Average leaf area per node (mm^2) was measured with the use of a planimeter and based on a cumulative sample of 20 fully expanded leaf pairs. Measurements were repeated over two consecutive sequential harvests to ensure measurement of fully expanded leaves.

IV.3.3 Results:

The production of nodes per plant was linearly related to thermal time from emergence for each of the five plant density treatments (Figure IV.3.1).

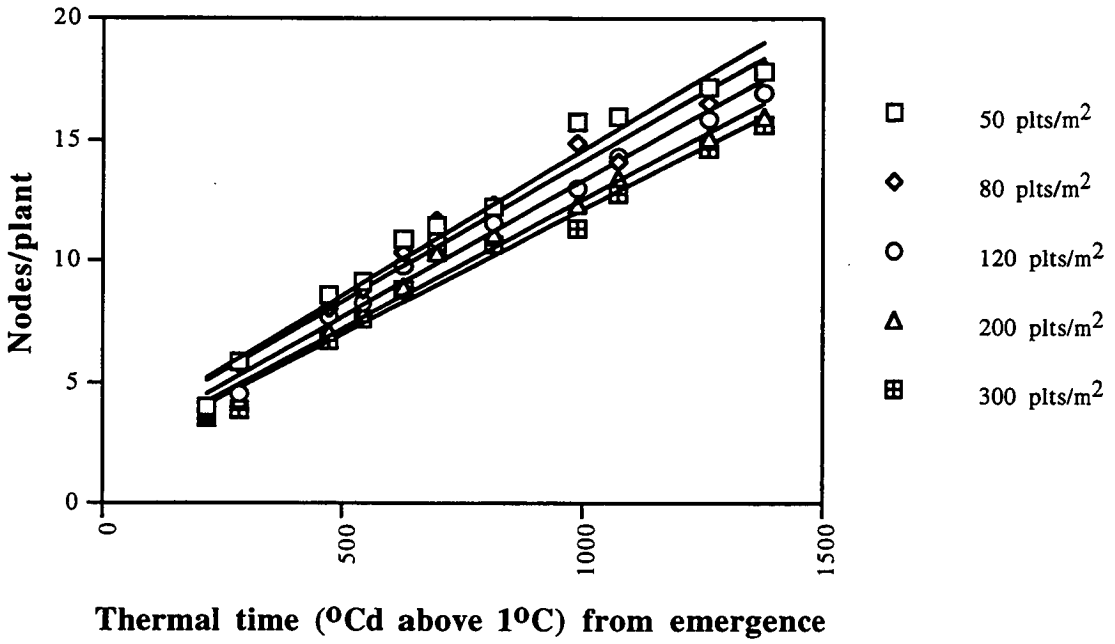


Figure IV.3.1: Response of node number per plant to thermal time (°Cd) above a base temperature of 1 °C. Linear regression lines are shown for each density treatment and are in order from 50 plants/m^2 (top) to 300 plants/m^2 (bottom).

The thermal time requirements for node production (reciprocal of the slope of thermal time response plot) were 84, 87, 89, 94 and 97 °Cd/node (above a base temperature of 1 °C) for the 50, 80, 120, 200 and 300 plant per m² treatments respectively (Figure IV.3.2).

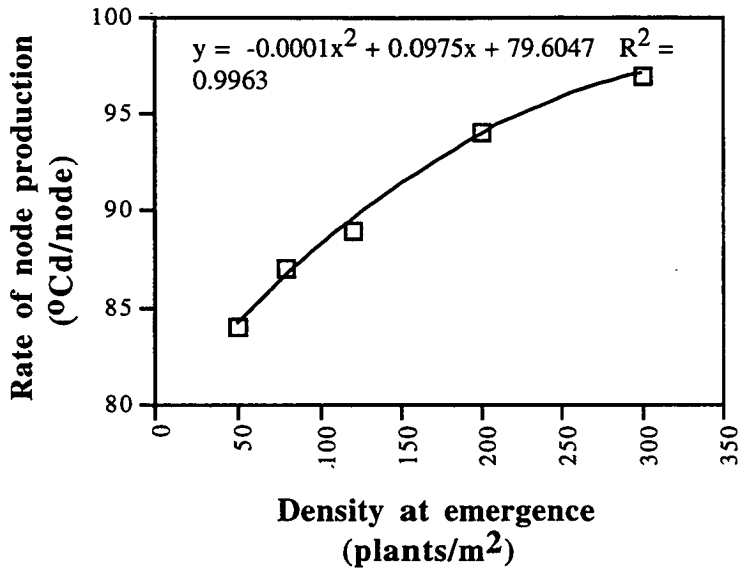


Figure IV.3.2: Response of thermal time for node production (°Cd/node) to density at emergence (plants/m²). The fitted second order polynomial is also shown.

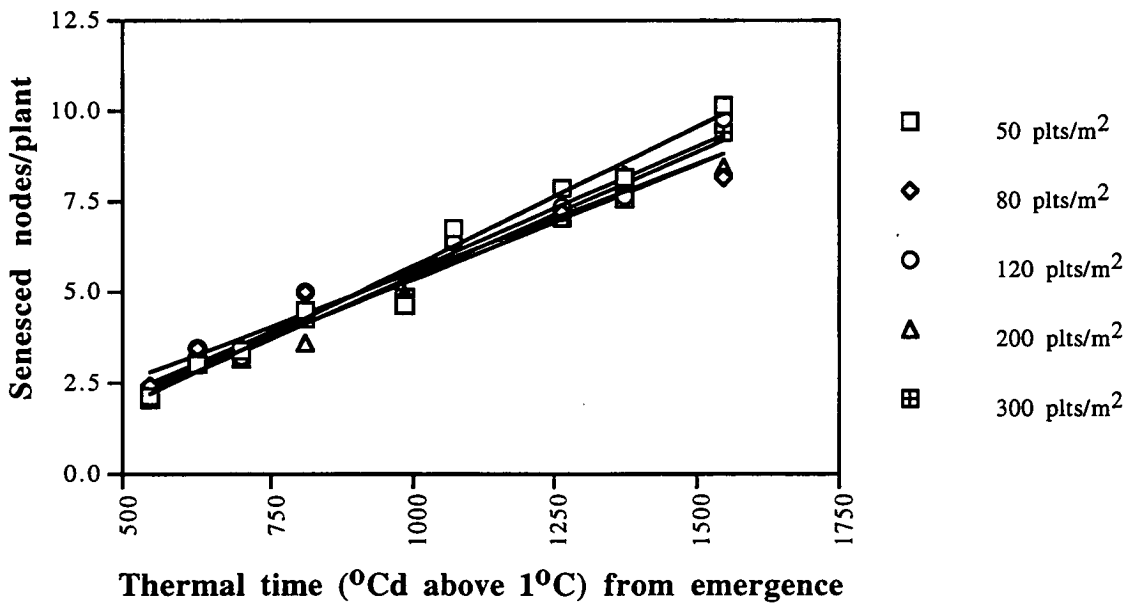


Figure IV.3.3: Response of senesced node number per plant to thermal time (°Cd) above a base temperature of 1 °C. Linear regression lines are shown for each density treatment.

The number of nodes from which leaves had senesced also increased linearly with thermal time from emergence (Figure IV.3.3). Thermal time requirements for node senescence for the 50, 80, 120, 200 and 300 plants per m^2 treatments were 130, 167, 145, 156 and 145 ^oCd/senesced node respectively.

At each of the five plant density treatments, leaf area per node at first increased linearly with node number, reached a plateau, and subsequently declined linearly (Figure IV.3.4). Systat 5.2.1 statistical software was used to fit linear regressions to the increasing and decreasing portions of this response. The maximum leaf area (plateau) was taken as the average of the nodal leaf areas within this phase. These equations were then used to obtain estimates for the cardinal node numbers (N1, N2, N3 and N4) which describe the leaf area per node response (Table IV.3.1). N1 and N4 define the lower and upper limits of the increasing and decreasing phases respectively. N2 and N3 define the transition points between the three phases.

Table IV.3.1: Cardinal node numbers and maximum leaf area per node (mm^2) for each of the five density treatments.

Plant density	Lmax	Cardinal node numbers:			
(plants/m^2):	(mm^2):	N1	N2	N3	N4
50	14146	1.6	4.3	10.4	20.2
80	11938	1.7	4.3	13.3	19.0
120	9973	1.5	4.2	12.5	19.8
200	9108	1.1	4.8	12.3	17.6
300	7368	1.2	4.3	11.9	17.1

Estimates for N1 and N2 varied by a fraction of one node across the five plant populations. The variation in N3 and N4 with plant population was larger at about three nodes for each parameter. In the hemp model described in the following chapter, the sensitivity of predicted leaf area to changes in N3 and N4 of this magnitude was found to be negligible (<2%). Consequently, the cardinal node numbers adopted in the model were averaged across the five plant populations.

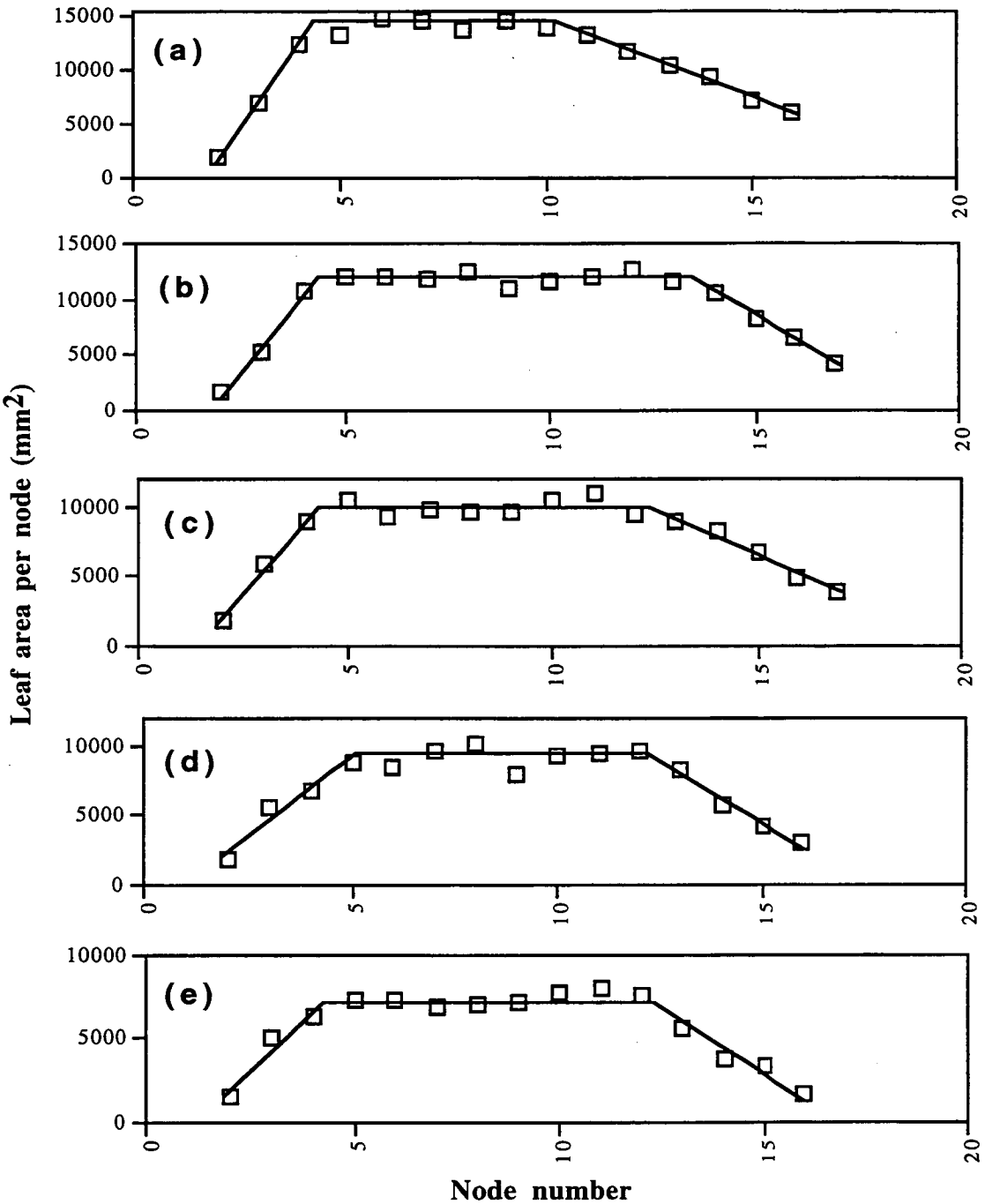


Figure IV.3.4: Leaf area per node (mm^2) versus node number for the 50 (a), 80 (b), 120 (c), 200 (d) and 300 (e) plant per m^2 density treatments.

The maximum leaf area (lmax) declined substantially with plant population at emergence and was found to have a significant influence on leaf area prediction (Chapter IV.4). A second order polynomial fitted to the lmax response to population ($y=0.106x^2-61.494x+16487.360$) accounted for 95% of the variation in lmax.

IV.3.4 Discussion:

Leaf pairs (nodes) appeared and subsequently senesced at constant thermal time durations. Similarly, leaf area per node varied in a simple, piecewise linear manner. The effects of plant density on node appearance and maximum leaf area per node were readily approximated by curvelinear functions. These relationships are used to simulate leaf area production in the hemp model, described in the following chapter.

The increase in the thermal time requirement for node appearance (°C.d/node) with plant population has previously been observed by van der Werf *et al.* (1995). Kompolti Hybrid TC was grown in the Netherlands over two seasons at four different populations, including 10, 30, 90 to 270 plants/m^2. The durations averaged over the two seasons were 54, 58, 73 and 92 °C.d/node (above a base temperature of 1 °C) respectively (H.M.G. van der Werf, unpublished data). At similar plant densities, these reported values are generally less than those observed for this current trial. Such differences might be attributable to genotypic variation between the two cultivars.

The thermal time requirements for node senescence were generally larger than for node appearance. This is reflected in the increase in leaf area index up to flowering observed for the 50, 80, 120 and 200 plants per m^2 treatments. In contrast to node appearance, the thermal time requirement for nodal senescence did not show any apparent trend with population. The limited number of senescence data points available from the Dutch population trial (four per treatment for the 1992 trial) did however suggest an increase in duration with population (H.M.G. van der Werf, unpublished data). More extensive senescence data at a single population of 90 plants per m^2 was collected from Dutch studies into the response of Kompolti Hybrid TC to daylength (van der Werf *et al.* 1994). Results for two seasons were 135 and 156 °C.d/senesced node (above 1 °C), compared with 167 °C.d/senesced

node (above 1 ^{o}C) for the same density of Kompolti in this current trial.

IV.4 Hemp simulation model.

IV.4.1 Introduction:

New crop evaluation has traditionally involved time and cost intensive agronomic studies. Additionally, in the case of a crop such as hemp, there are political, social and security implications associated with cultivation. The extent of such studies might potentially be reduced with the use of a simulation model that is able to accurately predict performance under varying environmental and management conditions. Such a model would be particularly valuable in the initial assessment of cropping potential at a given location. If promising, the model could then be used to assist in identifying optimum site and management conditions and the nature of further agronomic studies.

This section describes a computer model for simulating the growth, development and yield of hemp in response to climatic, soil and management inputs.

The hemp model has been developed within the framework of a larger systems model known as APSIM, or the Agricultural Production System Simulator. APSIM has been developed by the Agricultural Production Systems Research Unit (APSRU) based in Toowoomba, Australia. A detailed description of APSIM is reported in a paper by McCown *et al.* (1996).

APSIM simulates agricultural production systems by combining modules describing the specific processes within each system. Modules are either biological (eg crop, pasture, surface residue), environmental (eg water balance, nitrogen balance, soil erosion), managerial (eg tillage, irrigation, fertilisation) or economic. Selected modules are plugged into the APSIM " engine" which passes information between modules according to a standard protocol. The ability of APSIM to simulate agricultural systems is made possible by having as its central concept, that of the soil responding to weather, management and crops, rather than the crop responding to resource supplies (Meinke *et al.* 1996).

The hemp crop module was developed from a standard APSIM crop template (McCown *et al.* 1996). Many of the natural processes described by the template code are common for a range of crops and hence only a small number of

modifications were required to develop a code specific to hemp.

IV.4.2 Experimental datasets:

The hemp module has been developed and validated for the cv. Kompolti, using datasets collected from a range of trials described in Table IV.4.1. The controlled environment trials (Trials 6 and 7) were used to develop key model parameters and constants relating to pre- and post-emergent phenology. Inputs relating to leaf area production and biomass partitioning were obtained from the plant density trial (Trial 3). The remaining independent datasets were used to validate the model. Detailed descriptions of these trials are given in previous chapters.

IV.4.3 Description of model processes:

The key parameters and constants used to specify the processes of the hemp module are listed in Table IV.4.2. These inputs are externalised from the main model code in separate parameter and constant files. This enables ready modification of the model without the need for re-writing complex code.

Phenology:

The APSIM crop template divides crop phenology into eight phases. Since hemp is harvested at the late flowering stage, just five of these phases are relevant. They include: (a) sowing to emergence ((i) sowing to 50% germination, (ii) lag and (iii) linear phases of hypocotyl elongation); (b) emergence to the end of the basic vegetative phase; (c) a photoperiod induced phase ending at 50% floral initiation; (d) 50% floral initiation to 50% flowering; (e) 50% flowering to final harvest (50% of males releasing pollen). Full descriptions of these phases and the parameters and constants that describe them are detailed in Chapters IV.1 and IV.2.

In the model, daily thermal time is accumulated within each phase until a target thermal time duration is reached, whereupon development progresses to the next phase. The duration of phases other than the pre-emergence linear elongation sub-phase and the photoperiod induced phase, are predicted from set thermal time targets. The duration of the linear elongation phase is based on sowing depth (mm) and a set thermal time for 1mm elongation of the hypocotyl. The duration of the photoperiod induced phase is determined by the cultivar specific photoperiod sensitivity.

Table IV.4.1: Trials incorporating cv. Kompolti and used in the development and validation of the hemp model.

No.	Location	Sowing date.	Reference chapter.	Treatments
1	Forthside, Tas.	21.9.94 10.10.94 24.10.94 08.11.94	II.2	Sowing date (4)
2	Cambridge, Tas.	30.5.94 14.10.94 2.11.94 17.11.94	II.2	Sowing date (4)
3	Forthside, Tas.	26.9.95	II.3	Plant density (5)
4	Forthside, Tas.	26.9.95	II.4	Irrigation (5)
5	Forthside, Tas.	17.10.95	II.1	Cultivar
6	Laboratory	1996	IV.1	Pre-emergent development vs temperature
7	Glasshouse	1996	IV.2	Phenology vs photoperiod
8	Forthside, Tas.	03.10.96 23.10.96 06.11.96	II.2	Sowing date (3) x plant density (3)

Table IV.4.2 : Key parameters and constants for the hemp crop module.

	Units	Value
Pre-emergent phenology:		
Sowing to germination	^{o}Cd	24.1
Lag phase of hypocotyl elongation	^{o}Cd	44.5
Rate of linear hypocotyl elongation	^{o}Cd/mm	1.34
Post emergent phenology :		
Basic vegetative period	^{o}Cd	390
Photoperiod sensitivity	^{o}Cd/hr	251.8
Flower development period	^{o}Cd	80.2
Flowering to harvest	^{o}Cd	224.3
Maximum optimum photoperiod	Hours	13.8
Cardinal temperatures:		
Base temperature	^{o}C	1
Optimum temperature	^{o}C	28
Maximum temperature	^{o}C	40
Biomass production:		
Node production rate (50-300 plants/m^2)	^{o}Cd/node	84-97
Node senescence rate	^{o}Cd/node	147
Cardinal node number N1		1.4
Cardinal node number N2		4.4
Cardinal node number N3		12.1
Cardinal node number N4		18.7
Maximum nodal leaf area (50-300 plants/m^2)	mm^2	14146-7368
Radiation use efficiency (pre/post flowering)	g/MJ PAR	2.2/1.1
Extinction coefficient (Meijer et al. 1995)		0.96
Biomass partitioning:		
Stem fraction of TDM		0.90
Leaf fraction of TDM (below/above 500g/m^2 TDM)		0.34/0.06
Water uptake:		
Transpiration efficiency	Pa	5
Extraction front velocity (pre/post emergence)	mm/day	5/15
Nitrogen uptake:		
Time constant for nitrogen uptake	Days	2

Biomass accumulation:

The prediction of potential daily dry matter production (DM, g/plant/day) is based on the amount of photosynthetically active radiation intercepted by the canopy (I, MJ/plant/day) and the efficiency with which this radiation is converted into biomass (radiation use efficiency, RUE, g/MJ).

ie DM = RUE * I.

The amount of radiation intercepted is calculated from Beer's law:

ie $I = I_o * \{1 - \exp(-k * L)\}$,

where, I_o is the amount of incident PAR, k is the extinction coefficient relating leaf angle to the ability of leaf area to intercept radiation, and L is the leaf area (green) index (Loomis & Connor 1992).

Leaf area production:

The simulation of leaf area production involves coupling the component processes of leaf appearance, leaf senescence and leaf expansion.

In the study of leaf area production described in Chapter IV.3, leaf pairs (nodes) were found to appear and senesce at constant thermal durations. Furthermore, leaf area per node (l_a) at first increased linearly with node number (n), reached a plateau (l_{max}) and subsequently declined linearly.

The model used to describe this response is of the form:

$l_a = 0$ $\quad 0<=n<=N1$ (1)

$l_a = -l_{max} * N1 / (N2-N1) + l_{max} / (N2-N1) * n$ $\quad N1<n<N2$ (2)

$l_a = l_{max}$ $\quad N2<=n<=N3$ (3)

$l_a = l_{max} * N4 / (N4-N3) - l_{max} / (N4-N3) * n$ $\quad N3<n<N4$ (4)

N1 and N4 define the lower and upper limits of the increasing and decreasing phases respectively. N2 and N3 define the transition points between the three phases (Carberry & Muchow 1992).

Initial plant density was found to have a substantial effect on both leaf appearance rate ($y=-0.0001x^2+0.0975x+79.6047$, $R^2=0.99$) and the maximum leaf area ($y=0.1x^2-61.5x+16487.4$, $R^2=0.95$). Linear interpolations of these curvelinear responses are incorporated within the hemp model. Model inputs for the cardinal

node numbers and the rate of senescence are average values for the five density treatments.

The node number at any given time is simulated as a function of thermal time from emergence. Potential total leaf area is then determined by adding the leaf area produced at each node, calculated using equations 1 to 4. The leaf area corresponding to senesced nodes (starting at n1) is then subtracted from this total to give the green leaf area.

The contribution to photosynthesis of plant parts other than leaves (ie petioles, stems & inflorescences) was not taken into consideration in the prediction of biomass accumulation.

Radiation use efficiency (RUE):
Radiation use efficiency was not measured in any of the trials conducted in Tasmania. Consequently, literature estimates were used in the hemp model for this parameter.

In trials with Fedrina 74 grown at two seeding rates, Meijer *et al.* (1995) reports that RUE declined rapidly from 2.2-2.0 g/MJ (ie grams of above ground dry weight per MJ of intercepted PAR) before flowering, to 1.1-1.2 g/MJ after flowering. This change was attributed to a decline in dry matter production resulting from an increase in canopy senescence and the synthesis of fat and protein in the seed.

The response of RUE to plant density is also reported by van der Werf *et al.* (1995a). In experiments conducted with Kompolti Hyper Elite, at plant densities of 10, 30, 90 and 270 plants/m^2, RUE decreased with increasing density from emergence to a time H1 (2.35, 2.07, 1.76 and 1.52 g/MJ); was unaffected by density from H1 to flowering (2.24, 2.28, 2.25 and 2.07 g/MJ); and was maximum for the 30 and 90 plant per m^2 treatments after flowering (1.12, 1.9, 1.96, 1.31 g/MJ).

Based on these reports, the values of RUE selected for use in the model were 2.2 g/MJ PAR for the basal vegetative period, photoperiod sensitive phase and floral initiation phase, and 1.1g/MJ PAR for the short period between flowering and

harvest.

Allowance for possible density effects on RUE would require modification of the main code, with the inclusion of a response function describing this effect. Whilst the above report of van der Werf *et al.* (1995a) indicates a density effect, it is not possible to develop such a function from the available data. The effect of the above mentioned response was investigated by changing the basal vegetative phase RUE from 2.0 to 1.5 g/MJ for the high density treatments of Trial 3 (Table IV.4.1). This had a negligible effect (<0.5%) on predicted total dry matter.

Light extinction coefficient (k):
Throughout the course of the plant density trial (Chapter II.3), measurements of light transmitted through the canopy were made at fortnightly intervals. Three tube solarimeters were positioned across the plot at ground level and connected in series to a Delta Instruments Type MV1 integrator. Readings were collected over a 5 minute period around 11:30 am-12:30 pm. Percent transmission was then determined by comparison with total incident radiation measured in uninterrupted sunlight. Data was collected from four replicate plots and then averaged to give the final result.

Plots of the natural logarithm of percent transmitted light against leaf area index demonstrate the expected decline in light transmission through the canopy, with increases in LAI (Figure IV.4.1). The light extinction coefficient (taken from Beer's Law as the slope of this response) generally decreased with increasing density; from 0.573 at 50 plants/m^2 to 0.397 at 300 plants/m^2. These values of extinction coefficient are considerably less than the 0.96 reported by Meijer *et al.* (1995). Reasons for this difference are unclear. One possible cause may have been the narrow plot width used in the plant density trial which allowed light to come in from the inter-plot gap.

A sensitivity analysis was performed on the plant density trial dataset to investigate the response of predicted total dry matter to changes in the extinction coefficient. Biomass was consistently underpredicted with a value of k=0.42, the average across the five density treatments. The higher value reported by Meijer *et al.* (1995) gave an excellent fit between observed and predicted results.

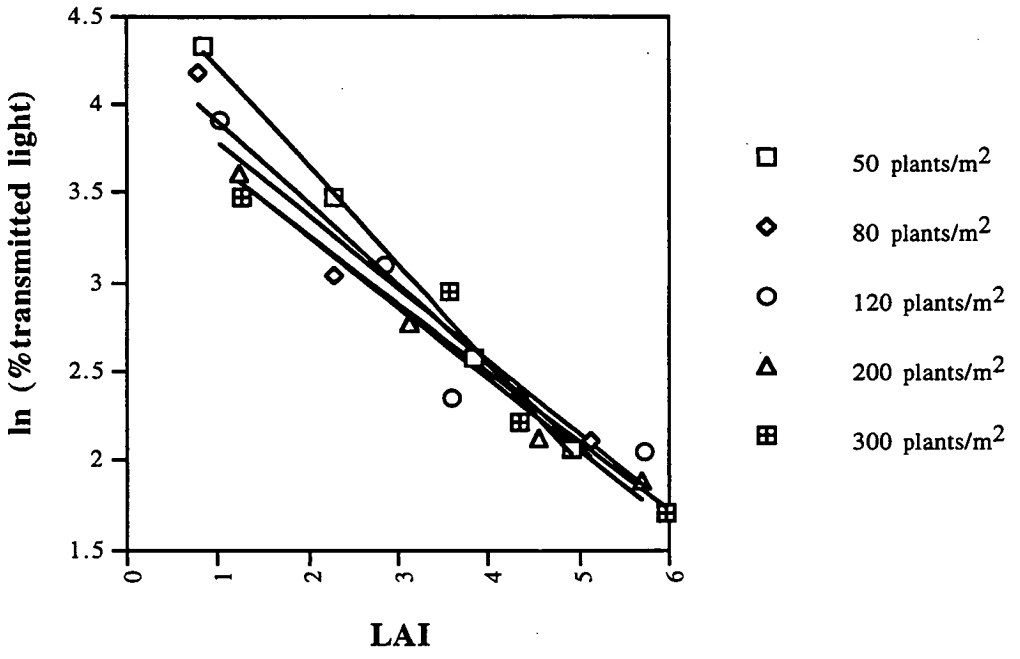


Figure IV.4.1: Plots of ln (% transmitted global solar radiation) versus leaf area index. Linear regression lines are shown for each density treatment reported in Chapter II.3.

Biomass partitioning:

The partitoning coefficients used in the model were based on sequential and final harvest data collected from the plant density trial reported in Chapter II.3. Plots of stem and non-stem (leaf and floral matter) dry matter versus above ground total dry matter are shown in Figure IV.4.2.

The linear model fitted to the stem vs total dry matter plot ($y=0.90x-72.19$, $R^2=0.996$) accounted for a large portion of the variation in stem fraction. This reflects the absence of significant differences in stem fraction between density treatments for all except the first harvest.

The partitioning fraction for the proportion of bark in the stem is based on a linear model ($y=0.43x-32.04$, $R^2=0.963$) fitted to a plot of bark yield versus stem yield (not shown).

The effect of phenology on stem fraction was minor and consequently, the model partitioning coefficient for stem is derived from the linear regression fitted to the

entire data set.

The leaf versus total dry matter plot was modelled in two phases by fitting linear regressions to the data points below and above 500g/m^2 total dry matter; y=0.34x+20.08 (R^2=0.968) and y=0.06x+127.74 (R^2=0.736) respectively. Leaf partition coefficients used in the model are taken from these equations.

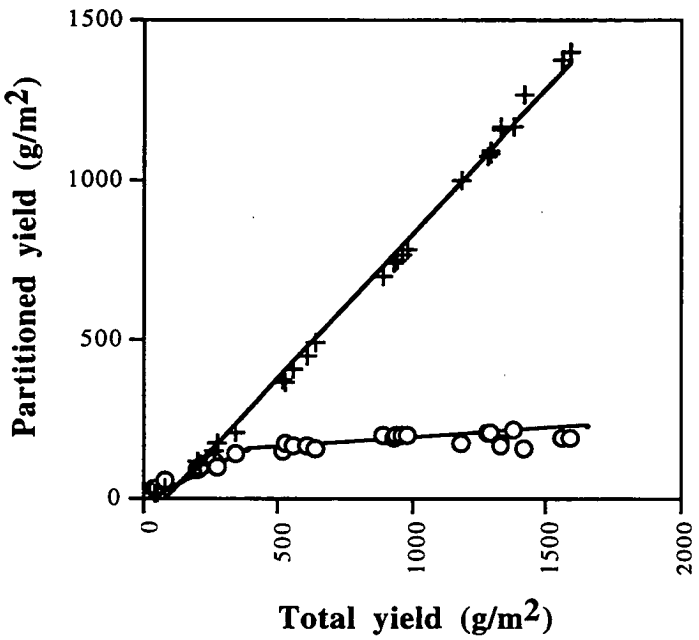


Figure IV.4.2: Stem (+) and non-stem dry matter (g/m^2) (o) vs total dry matter (g/m^2) for the plant density trial reported in Chapter II.3.

Water balance:

In APSIM, water uptake by a crop on any given day is the lesser of either the potential water supply or soil water demand.

Water supply:

Daily potential water supply is dependent on the depth of roots, the available water range of the soil and the potential rate of water extraction by the crop.

At any given time, the rooting depth or the depth to which water is extracted, is predicted from the rate of vertical root penetration (extraction front velocity). Variation in root distribution (and hence water uptake) through the various soil

layers is accounted for by a root distribution weighting factor.

The maximum amount of water available for extraction is calculated as the difference between the crop specific lower limit (LL) of extraction and the soil specific drained upper limit (DUL). The lower limit is the lowest volumetric soil water content at which the crop is able to extract water and is usually measured from the soil profile of a well developed, severely water stressed crop. The drained upper limit is the maximum volumetric soil water content remaining after the soil has been drained of free water. To account for changes in the water holding characteristics with soil depth, the profile is divided into layers, with each assigned values for LL, DUL and saturated volumetric soil water content (Probert *et al.* 1997).

To determine the amount of water supplied to the crop on any day, the total available water above the lower limit for all soil layers with roots is summed. If roots are only partially through a layer, available soil water is scaled to that portion which contains roots. A constant referred to as the kl constant (differs for each soil layer) is then used to limit the amount of available water on any day. The kl factor is empirically derived, incorporating both plant and soil factors which limit the rate of water uptake.

Water demand:
The potential daily transpiration (T, mm) of the crop is calculated as;
T = DM*VPD/TE (5), where DM is the potential dry matter production (g/m^2), VPD is the predicted daily vapour pressure deficit (Pa) and TE is the crop specific transpiration efficiency (Pa). The unconventional unit of pascal for transpiration efficiency is derived from TE=DM*VPD/T, where 1 cm^3 of water weighs 1 g.

Water deficits affecting plant growth:
Soil water deficit factors are calculated to simulate the effects of water stress on different plant growth processes. Four water deficit factors are calculated which correspond to four plant processes, each having different sensitivity to water stress, ie photosynthesis, phenology, leaf expansion and nitrogen fixation. Only the first three of these factors are relevant for hemp.

Other water related processes:

Other soil water processes such as evaporation and the flow of soil water under saturated and unsaturated conditons are also simulated by APSIM. These processes and the APSIM soil water module (SOILWAT) are discussed by Probert *et al.* (1997).

Hemp model inputs:

Water related inputs for the hemp model were not adequately measured in any of the trials conducted at Forthside. Consequently, parameters were taken from an existing APSIM dataset for a krasnozem soil on the Atherton Tablelands in northern Qeensland. Lower limit values were derived from a maize crop grown on this same soil. Transpiration efficiency was taken as 5 Pa, based on reported values for other C3 crops (Tanner & Sinclair 1983). The extraction front velocity was set at 5 mm/day for pre-emergent growth and 15 mm/day for post emergent growth. This assumes a total root depth of 1.8 m and a 120 day duration from sowing to flowering. Starting values for soil water content were set at 80% of field capacity.

Nitrogen balance:

Simulation of the nitrogen balance also involves relationships describing supply and demand. Uptake of nitrogen from the soil is simulated as a function of passive uptake of soil nitrate in the transpiration stream and active uptake, as determined by a time constant for diffusion. Crop demand depends on critical plant concentrations of nitrogen. When demand exceeds supply, a multiplying factor (0-1) modifies biomass accumulation.

In the absence of hemp specific parameters, the diffusion constant was set to two days (a common value for many crops) and the critical nitrogen concentrations were made equivalent to those for maize.

IV.4.4 Other model inputs:

Meteorological data:

Meteorological data for each season and location described in Table IV.4.1, were entered into separate files. At Forthside, daily temperature, rainfall, solar radiation and bright sunshine hour data were derived from a weather station positioned no more than 500 m from each trial location. Monthly correlations between bright

sunshine hours and global solar radiation were used to estimate daily radiation accumulations for the 1994-95 and 1995-96 seasons. The correlations were based on daily figures collected at the Hobart Airport over a four year period (Table IV.4.3). The installation of a solarimeter at Forthside in 1996, enabled direct measurement for the 1996-97 trial.

Daylength measurements required for prediction of flowering time in APSIM are calculated automatically from the trial latitude (model input) and the day of the year.

Table IV.4.3: Monthly (October to February) regression equations for global solar radiation (MJ/m^2) versus bright sunshine hours at the Hobart Airport. Equations are based on daily figures over a four year period from 1988 to 1991.

Month	Regression equation	R^2
September	y = 1.18x + 5.68	0.82
October	y = 1.45x + 7.51	0.86
November	y = 1.57x + 9.46	0.87
December	y = 1.60x + 10.75	0.85
January	y = 1.75x + 7.82	0.91
February	y = 1.46x + 8.79	0.87

Management inputs:

Management inputs required for the running of the hemp model include sowing date, irrigation and fertiliser inputs, sowing depth and sown population. This information was entered into separate files for each trial.

IV.4.5 Model testing:

Verification:

Prior to validation against independent datasets, the performance of the model was first assessed against observed data from the plant density trial (Chapter II.3), from which model parameters relating to leaf area production and biomass partitioning were developed. The accuracy of the model was determined from the coefficient of determination (R^2). Bias was indicated by the standard errors for the slope and y-intercept terms (significantly different from 1 and 0 respectively).

Verification plots for leaf area index, stem yield and total dry matter are shown in

Figures IV.4.3, IV.4.4 and IV.4.5 respectively.

The model accurately predicted stem yield and total dry matter across the five plant density treatments used in this trial. Prediction of leaf area index was less accurate but still satisfactory.

There was evidence of bias in the prediction of the three variables, with the model tending to overpredict at low values and underpredict at high values.

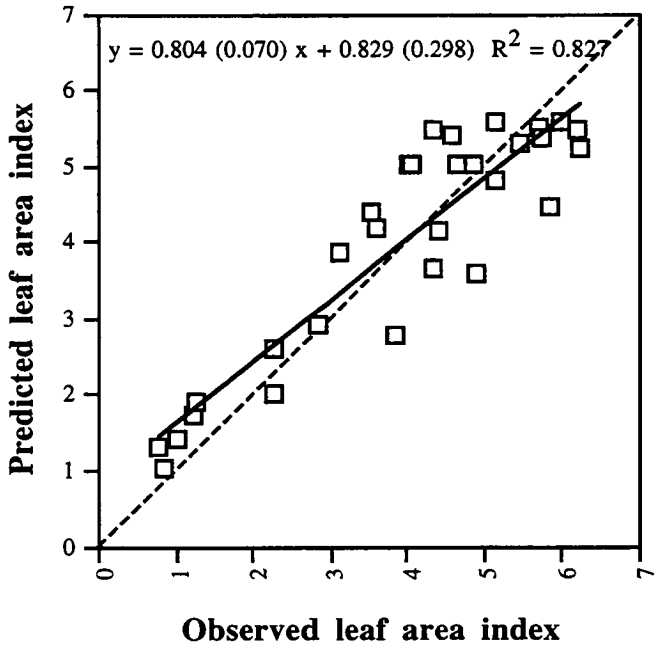


Figure IV.4.3: Verification plot of predicted leaf area index versus observed leaf area index. (-) Fitted linear regression & equation (standard errors are bracketted). (--) 1:1 line.

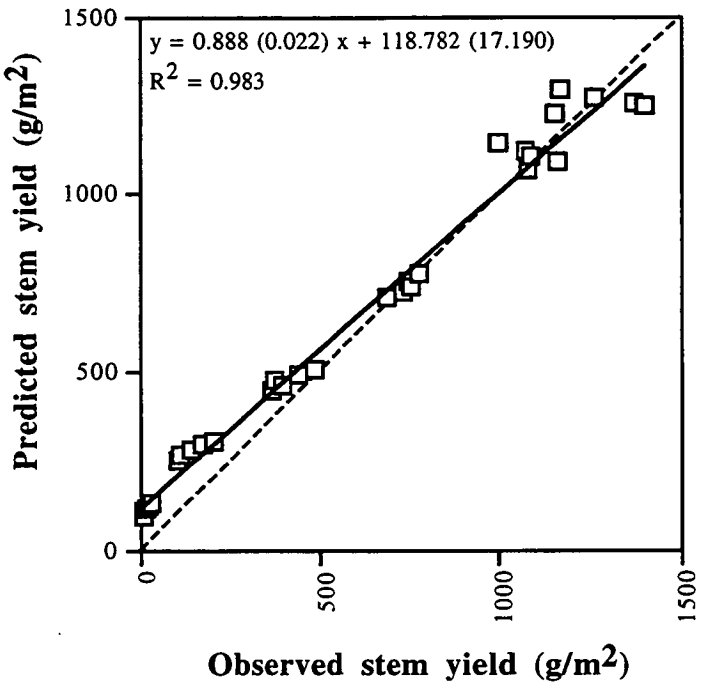


Figure IV.4.4: Verification plot of predicted stem yield (g/m^2) versus observed stem yield. (-) Fitted linear regression & equation. (--) 1:1 line.

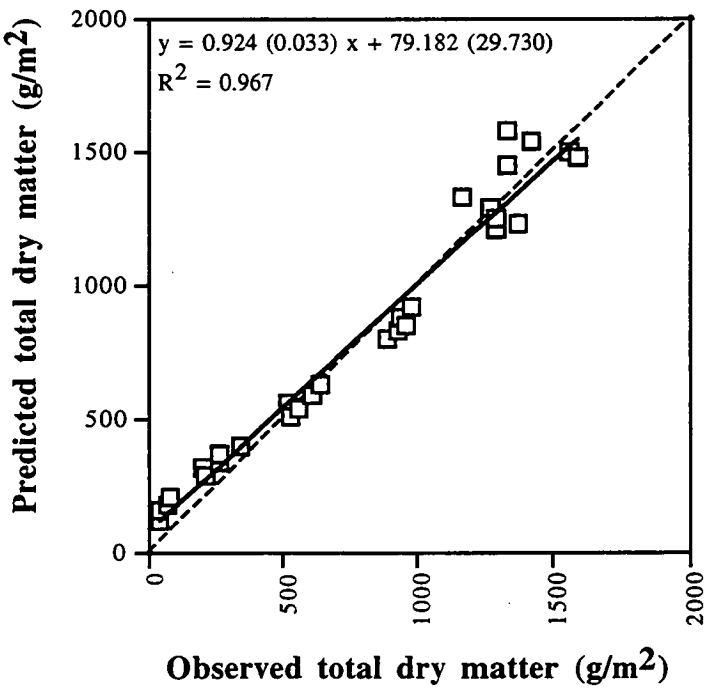


Figure IV.4.5: Verification plot of predicted total dry matter (g/m^2) versus observed total dry matter. (-) Fitted linear regression & equation. (--)1:1 line.

Independent datasets:

Predicted and observed thermal times from sowing to flowering are compared in Figure IV.4.6. The results are from nine sowing dates at Forthside and four at Cambridge. Observations of flowering date made with the naked eye were discounted by 3 days to make them equivalent to the observations based on dissection (Chapter II.2). The fitted equation (y=0.856(0.241)X+10.971(20.245)) accounted for 82.5% of variation over all datasets, which is at the higher end of model prediction accuracy. The data points from Cambridge were grouped together beneath the 1:1 prediction line and were separate from the Forthside data points. This may suggest that factors other than daylength influenced the time of flowering.

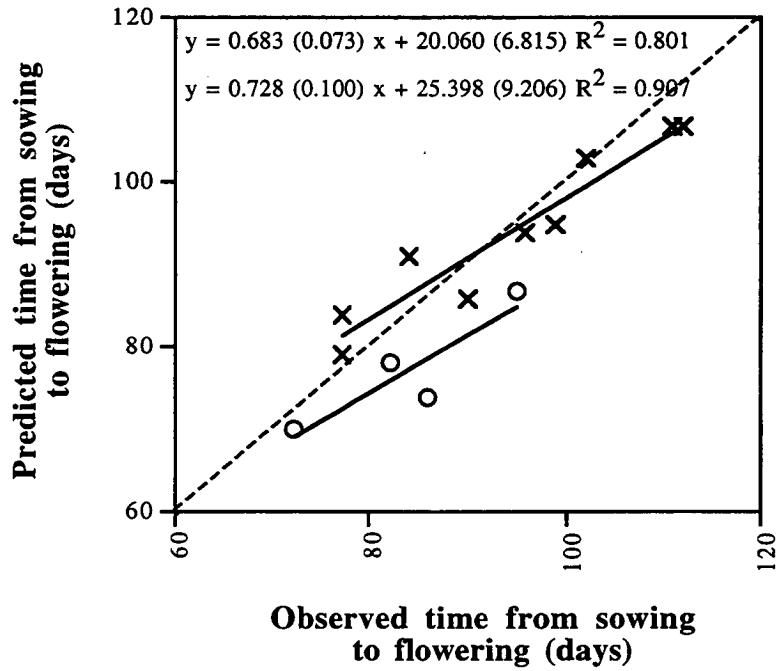


Figure IV.4.6: Predicted versus observed flowering time (days after sowing) for Kompolti sown at Cambridge (o) and Forthside (x). (-) Fitted linear regressions & equations for each site. (--) 1:1 line.

As for the plant density trial described above, predictions of leaf area index were less precise than for stem yield and total dry matter (Figure IV.4.7). However, the model still accounted for approximately 70% of the variation in observed leaf area index across all independent datasets. Within the trials used for this validation, there were few observations of indices below 4. More data in this range would have been beneficial for validation.

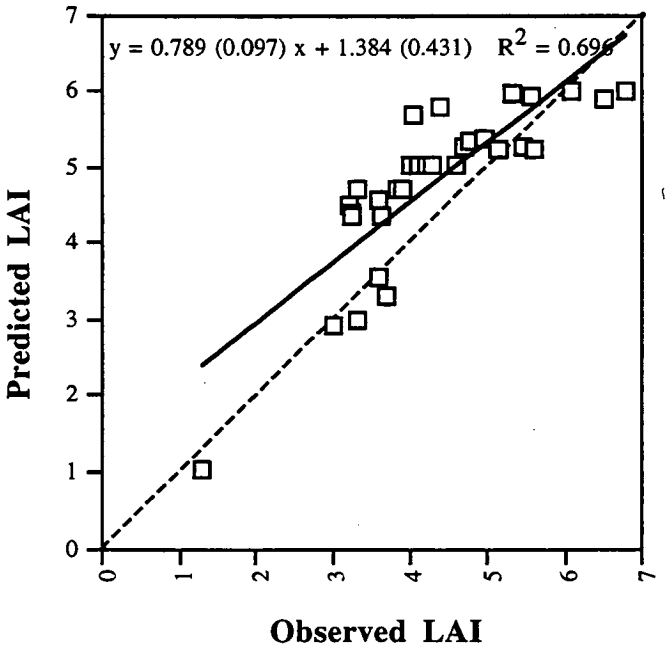


Figure IV.4.7: Validation plot of predicted leaf area index versus observed leaf area index. (-) Fitted linear regression & equation. (--) 1:1 line.

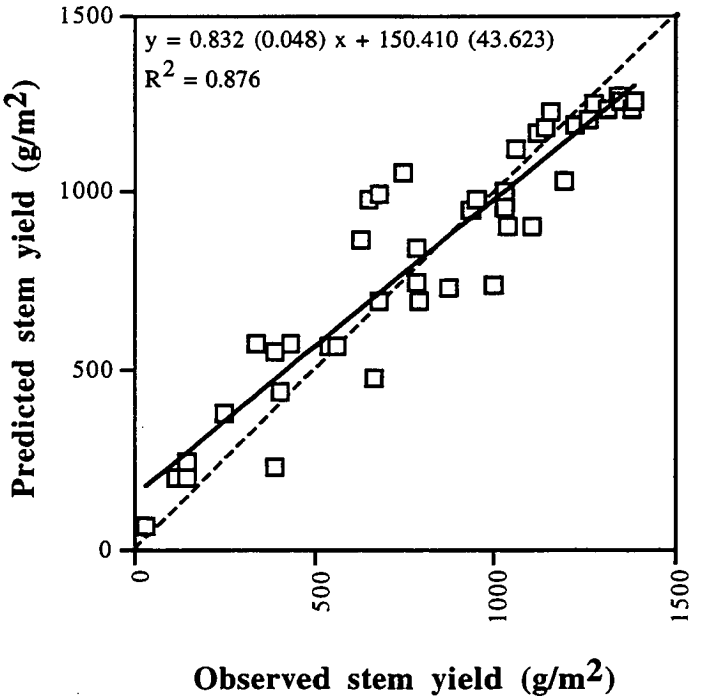


Figure IV.4.8: Validation plot of predicted stem yield (g/m2) versus observed stem yield. (-) Fitted linear regression & equation. (--) 1:1 line.

Validations of predicted versus observed stem yield and total dry matter are shown in Figures IV.4.8 and IV.4.9 respectively. Accounting for 88% of the variation in stem yield across all Forthside datasets, the degree of accuracy in prediction is comparable to other APSIM crop modules (Carberry 1995). As with the model verification plots, there was evidence of an apparent bias in the validation plots, with the model tending to overpredict at low values and underpredict at high values.

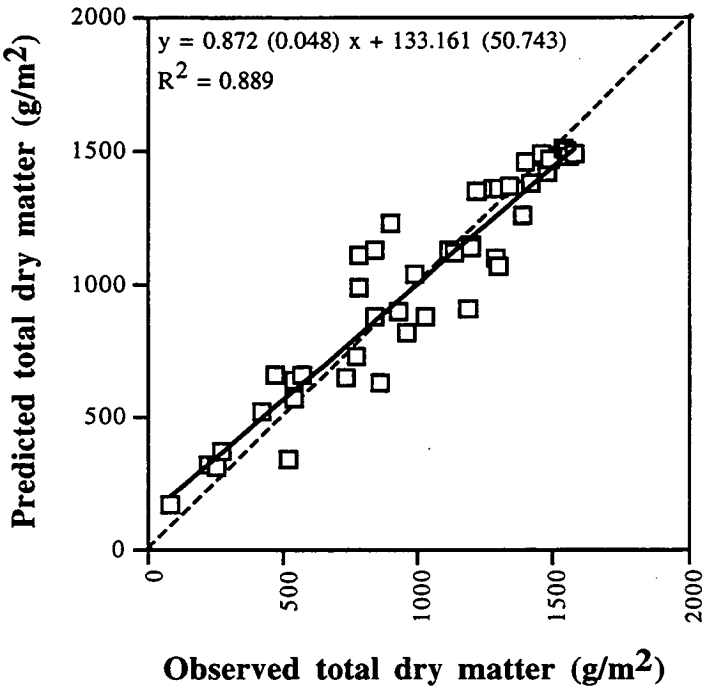


Figure IV.4.9: Validation plot of predicted total dry matter (g/m^2) versus observed total dry matter. (-) Fitted linear regression & equation. (--) 1:1 line.

IV.4.6 Discussion:

The hemp model adequately predicted phenology, leaf area and biomass production for the cultivar Kompolti at Forthside. Predictions were sound across a range of independent datasets collected over three seasons and including treatments of sowing date, irrigation regime and plant density. Nevertheless, this represents a limited range of environments and in order to assess the broader suitability of the model, its performance will need to be assessed over a range of other site and management conditions.

Total dry matter and stem yield predictions were generally better than for

phenology and leaf area prediction. A degree of bias was apparent for all variables with a tendency to underpredict at low values and overpredict at high values.

Improvement in the accuracy of phenology prediction will require consideration of the influence of factors other than photoperiod on flowering. These might include plant nutrition, temperature (Heslop Harrison & Heslop Harrison 1969) and plant density (Chapter II.3 and van der Werf 1997). Furthermore, the scope of the model would be improved by the inclusion of photoperiod response parameters for other hemp cultivars.

The contribution to photosynthesis of plant parts other than leaves (ie petioles, stems & inflorescences) was not taken into consideration in the prediction of biomass accumulation. Of these nonlaminar sources of photosynthesis, the stem fraction is likely to be the most significant. Assuming an average stem width of 0.6 cm, an active photosynthetic stem length of 150 cm and a plant density of 100 plants/m^2, the maximum contribution to photosynthetic area from the stem fraction would be approximately 0.9 m^2. Given that the contribution of stem area to green area index (GAI) would increase with crop age, the extinction coefficient (slope of ln (%transmitted light) vs GAI) of the crop would also decrease. Future refinement of the model would require consideration of these influences.

Further consideration should also be given to disparities between the findings from this study and those of the Dutch, especially in relation to the extinction coefficient (Meijer *et al.* 1995) and the influence of plant density on the rate of senescence (H.M.G. van der Werf, unpublished data).

A limitation with the development and validation of the model was insufficient soil and crop specific data relating to soil water and nitrogen availability and uptake. This has been a common deficiency with other crop models that have been developed within the APSIM framework. Research collaborators with APSRU are now being encouraged to incorporate collection of the appropriate data as part of their trial activities (Carberry 1995). Whilst the performance of the hemp model was satisfactory using parameter estimates derived from other non-hemp datasets, accurate prediction over a range of growing conditions and especially under water or nutrient limiting conditions, will require more site and crop specific data.

The high susceptibility of hemp to waterlogging, especially at the seedling stage, has been reported in other recent Australian field trials (Beetson & Smart 1997, Lolicato *et al.* 1996). This, coupled with the fact that hemp grown in Australia would need to be irrigated (at least in southern Australia), suggests that the development of functions to simulate the effects of soil and free surface water on seedling mortality would be a valuable model inclusion.

With further refinement and expansion, the hemp crop model has the potential to be a valuable tool for investigating yield potential under a range of growing conditions. As an element of the APSIM framework, this simulation capability can be extended to encompass the broader cropping system in which hemp is incorporated.

Section V: Utilisation of fibre hemp and flax as a source of pulp for newsprint production in Tasmania.

V.1 Introduction:

The Tasmanian operation of Australian Newsprint Mills Ltd (ANM) produces approximately 40% of Australia's newsprint and related paper grade requirements. The primary raw materials are eucalypt and radiata pine logs. More recently, recycled newsprint pulp produced at ANM's Albury mill has been used in paper manufacture at the Tasmanian mill.

The pine component is pulped using a thermomechanical (TMP) process in which woodchips are softened with exposure to high temperature steam and then pulped in a disc refiner.

The hardwood component is pulped using a cold caustic soda (CCS) process in which the woodchips are steamed, compressed, impregnated with caustic soda and then reduced to pulp in a disc refiner. This is essentially a chemimechanical (CMP) process with a mild steam cooking phase.

The resultant pulps are then blended with a small amount (up to 15%) of imported, kraft (chemical) pulp (Figure V.1.1), the purpose of the supplement being to provide additional strength to the paper. This supplement requirement amounts to approximately 20,000 tonnes per annum and is sourced from Canada (based on spruce) and New Zealand (based on radiata pine).

The primary aim of the pulping trials described here was to investigate the potential of using flax and hemp bark and whole stem pulps as alternative reinforcing agents in newsprint production. The existing CCS and TMP processes were trialled with a view to harnessing the existing infrastructure and expertise.

Potentially, ANM would benefit from being able to source and process the required strengthening supplement locally, thus reducing their vulnerability to market fluctuations in the price and availability of kraft pulp. Local supply would also

provide a substantial boost to the Tasmanian economy.

Pulps were also made from the core fraction to assess its suitability as a supplement to the short fibred eucalypt component of the existing newsprint blend. Additional returns from the sale of the core fraction would improve the economic viability of a future industry (see Section VI).

Pulping research in Tasmania:

In 1993, Australian Pulp and Paper Mills (APPM) and ANM conducted preliminary laboratory pulping trials with hemp straw grown at the University of Tasmania Farm (Wolfgang Spielmeyer pers. comm. 1994), using chemical and thermomechanical processes, respectively.

APPM concluded that the only viable chemical pulping option would involve processing the separated bark fraction to produce a specialty pulp. Hemp core and whole stem pulp were said to be unsuitable for commercial papermaking due to very low freeness and air permeance (Maddern 1993). Maddern and French (1994) state that while chemically pulped hemp and flax are suitable for use as reinforcing agents in a broad range of commercial papers, there are a number of technical and financial obstacles that need to be addressed for it to be competitive with long fibred bleached softwood market pulp. Processing difficulties include effective separation of bark and core, and fibre cutting to suitable lengths to prevent dispersion difficulties during pulp and papermaking. It was concluded that financial viability as a reinforcing pulp would depend on producing a whole stem chemimechanical pulp, to develop the reinforcing properties of the long bark fibres and allow the inclusion of the core material.

Preliminary laboratory trials at ANM using whole hemp stem cut to lengths of 5-6cm and pulped using a TMP process, gave a pulp with similar tear index but lower tensile index relative to radiata pine TMP pulp. There was a tendency for the bark fibres to form strings which could cause problems on paper machines and in screening. On the basis of these preliminary findings, together with promising results from the Netherlands with mechanical and chemimechanical pulping of hemp (see below), a decision was made to expand the pulping studies, thus providing the impetus for this current study.

Worldwide pulping status:

In 1992, 23 hemp pulp mills were in operation throughout the world in countries such as Spain, France, Turkey, India and China. Total production capacity was 80,000 tonnes per year. There were an additional 14 flax mills with a capacity of 75,000 tonnes per year (Judt 1992). These mills generally use separated bark fibre blended with other wood and non-wood pulps to produce specialty grades of paper. Commercial pressures have forced some mills to use whole stem or blends of whole stem and bark fibre in order to reduce costs (Jeyasingam 1990).

The raw material for flax mills generally comes from one of three sources. Waste material from spinning and weaving mills and linen rags are the purest form of flax fibres, free of core material. 'Flax tow' is the short bark fibre or waste product left over from the processing of the high quality textile fibre. This raw material is still relatively pure with only a small quantity of core material. The least pure form is 'seed flax tow' which refers to mechanically decorticated flax straw which has been grown primarily for seed. The content of core and other impurities depends on the efficiency of the decortication process but core levels are usually as high as 30-35%. The presence of these impurities, coupled with the fact that fibre flax vareties are bred and grown for optimum fibre quality, means that seed flax tow pulps are usually weaker and less durable than flax tow pulps.

The long, strong and slender fibres of flax are ideally suited for the production of thin strong papers. Flax pulp from textile flax tow is generally preferred for the production of currency papers and high quality permanent record and writing papers where strength and scuff resistance are required. Flax pulp produced from seed flax tow is used in cigarette paper manufacture (McGovern *et al.* 1987).

The properties of chemical hemp bark pulps are analogous to the equivalent flax bark pulp and are used interchangeably in the production of cigarette papers (Wong & Chiu 1995). Wong *et al.* (1993), conclude that the strength properties of chemical hemp bark pulp make it suitable for the replacement of standard bleached softwood kraft pulp as the general purpose reinforcement pulp for the manufacture of commodity papers.

Because of their long length, bark fibres have a tendency to tangle about each

other and within the workings of pulping equipment. This entanglement leads to problems with pulp flow through the mill and poor sheet formation characteristics in the final paper product (Wong & Chiu 1995). Consequently, traditional pulping of bark fibres begins with the cutting of the fibre prior to delivery to digesters for either sulphate or soda based chemical pulping. The fibres are cooked at elevated temperatures and pressure until the fibres are separated from each other. Once cooked, the chemicals and binding components are washed clear of the separated fibres. The fibres are then fed into a Hollander beater which simultaneously cuts the fibre to the desired length and roughens the fibre surface over a period of up to twelve hours. Bleaching is performed either within the beater or in separate tanks following beating. The bleached pulp is then delivered to the paper machine (Jeyasingam 1990, van Roekel 1994).

The major limitation of such a process is that beating with the Hollander beater drastically worsens the pulp drainage properties, resulting in slower operating rates for the paper machine. The cost penalty associated with such delays has made it difficult for these traditional specialty hemp paper mills to compete with modern wood fibre based mills in the production of printing and writing grades of paper.

This realisation has led to consideration of mechanical and chemimechanical processes for the pulping of bark fibre, in which fibre length is controlled in the pulping process itself, thus eliminating the need for a Hollander beater. Other potential advantages with such processes include higher yields, lower chemical and water use and lower effluent production compared with chemical processes (van Roekel 1994).

Modern wood based mechanical and chemimechanical pulping processes employ disc refiners. Improved results for the pulping of long agricultural fibres have been obtained with the use of an extrusion machine prior to refining. This machine was developed in France and cuts the fibre to a desired length without dramatically affecting pulp drainage properties (van Roekel 1994).

Hemp pulping trials using an extruder were recently conducted in Holland as part of a four year investigation into the potential of fibre hemp as a raw material for pulp

and paper production (van Roekel *et al.* 1995). They found that peroxide bleached mechanical pulps prepared using an extrusion pulping method were comparable to a chemical softwood pulp.

A number of workers have investigated the pulping potential of the core fraction of hemp. Bosia and Nisi (1977), found hemp core fibres to have substantial collapse capacity and able to produce pulps with good mechanical properties. They were able to produce CMP pulps suitable for use in kinds of paper where poplar pulp is currently used. De Groot *et al.* (1988), also showed that CMP core pulps are suitable for use in newsprint and board manufacture.

Thermomechanical pulping of hemp core has been found to produce test paper sheets with very poor strength properties (Lips 1993).

McGovern *et al.* (1987), report that the woody core of flax produces a pulp not unlike a weak hardwood pulp, although there is no mention of the pulping process employed.

V.2 Materials and method:

The stem material used in the following studies was sourced from the field trials reported in Sections II and III. While some of the sample preparation methods had to be adapted or developed, the pulping and testing equipment was the same as that normally used at ANM for wood based paper research. The preparation of the stem material and subsequent pulping were performed in conjunction with ANM research staff. The testing of pulp handsheets was conducted entirely by ANM staff.

V.2.1 Hemp pulping trials:

Preparation:

Before commencing laboratory pulping trials, it was first necessary to prepare sufficient quantities of raw material to cover the range of pulping conditions to be trialled. Preparation required two processes; the separation of the two stem components, and the cutting of the bark fibre component into the desired length for pulping.

The first attempt at preparation involved hand stripping the bark fibres from the

stem and subsequent cutting with a guillotine. At a later stage, traditional hackling, scutching and combing tools were employed to speed up the decortication phase. Both methods were clearly unsatisfactory for producing the quantities required for a proper series of pulping trials and a more efficient process was sought.

Stem material of the cultivar Kompolti was retted by soaking in a tank full of water for four weeks (during winter). This allowed micro-organisms to break down the organic glues within the stem, allowing easier separation of the bark fraction from the core fraction. After retting, the fibres were air dried and then fed through a five blade chaff cutter (Figure V.1.2). The stems were fed end on to the cutter blade to promote a uniform cutting length of 5-8 mm. Overlength pieces were screened off and fed back to the cutter. Despite this feedback stage, the cut length was relatively non-uniform. This was attributed to a proportion of the stem feeding through the cutting mechanism at an angle and too coarse a sieving screen in the feedback stage.

The cut straw material was then passed through a Wiley mill fitted with a 4.75 mm screen to create a more uniform and shorter fibre length (Figure V.1.2). In order to determine the optimal cutting length, the milled straw was passed through a series of nested sieves with progressively smaller gauges; ie 4.75 mm, 2.36 mm, 1.18 mm and 300 µm. The dust fraction below 300 µm was discarded and the remaining fractions processed in a Lampen mill (type of ball mill) for 35 minutes with NaOH on a basis of 6% of oven dry (o.d) fibre weight at 5% consistency (ie % solids or s.c) and room temperature. The pulps were made into handsheets for the testing of strength and formation characteristics. On the basis of these results, material unable to pass through the 1.18 mm sieve was retained for pulping trials. It was considered that the inclusion of smaller fractions would adversely effect the strength properties of the resultant pulps. The approximate yield of +1.18 mm fibre (bark + core) was 77%.

Separation of the cut (and decorticated) stem fractions was achieved in water, harnessing the tendency for the core fraction to float and the bark fraction to sink (Figure V.1.3) (Maeyer & Huisman 1994). Approximately 100 g of cut and sieved straw was placed in a 20 litre vessel and covered with about 18 litres of

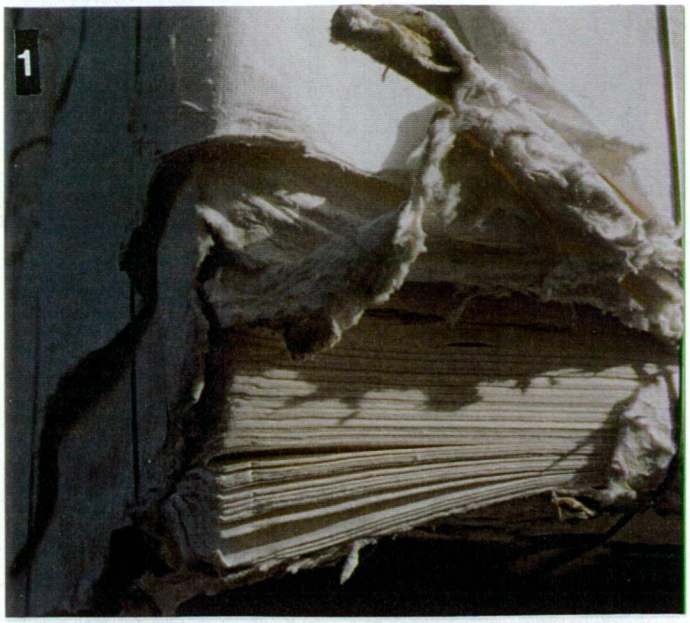


Figure V.1: (1) Open bale of kraft showing sheets of pulp. (2) Retted hemp stem (a) after passing through the chaff cutter (b) and then through the Wiley Mill (c). (3) Separation of core and bark fractions in water.

water. The combination was then thoroughly mixed with an electronic stirrer for 10 minutes. The speed of stirring was slowed gradually in the last few minutes to ensure gradual settling of the bark and to minimise the likelihood of the bark being trapped in the rising core. Too much of the straw or too little water resulted in less effective separation. The core was then skimmed off by hand into another vessel. The process was then performed again on each separated fraction to optimise the separation result. Finally, the fractions were drained of water and dried in readiness for pulping.

Core pulping trials:

Cold caustic soda pulps were made from core presoaked with NaOH on a basis of 5% and 10% of oven dry fibre weight. The percentage of solids in the pretreatments was 20%. The presoaking was conducted in a water bath for 1.5 to 3 hours at 47 °C. The mixtures were then diluted to 14-16% s.c. and refined in an Andritz Sprout Bauer 12-ICP pressurised laboratory refiner. A number of passes through the refiner were performed in order to generate pulps covering a range of freeness values. Mild steam cooking (69 kPa for 1 minute) and dilution prior to entry into the refiner were necessary in order to improve flow through the refiner and to lessen the chances of the material burning between the refiner discs.

Freeness is a measure of pulp drainage time, which in turn is a key determinant of the rate of dewatering in paper production and hence the speed at which the paper machine can operate. Additional refining tends to decrease the freeness of the pulp and slow the pulp drainage time. The freeness tester consists of a drainage chamber and a rate measuring funnel. The pulp to be tested is poured onto a screen plate in the drainage chamber. Water drains from the pulp and into the funnel, whereupon it flows through an orifice at the bottom of the funnel at a specified rate. Water which enters the funnel at a rate faster than that specified, overflows through a side arm and is measured to give the freeness value in millilitres (McKenzie 1994).

For thermomechanical pulping, a 20% s.c. mixture of oven dry core and water was presoaked in a water bath for 5 hours at 47 °C. The mixture was then steam cooked at 138 kPa for 3 minutes and refined at 16% s.c. to generate pulps with a range of freeness values.

The pulps were then delatentised to allow the strain induced in the fibre by refining to relax and hence improve sheet formation and strength characteristics. This process involved lowering the pulp consistency to approximately 2% and re-agitating at 80 °C.

Handsheets were made from each pulp after latency removal in order to assess and compare physical strength and surface characteristics.

Pulp fibre length distribution was measured using a Kajaani FS200 fibre length analyser. The same analyser was used to measure the length of fibres in the uncut core material and core that had passed through the chaff cutter and Wiley Mill. Samples were first digested in a solution of peracetic acid. These measurements enabled assessment of the effect of stem preparation on fibre length.

Bark pulping trials:

Pulps were prepared with the separated and cut bark fibre using similar processes to those described for the core fraction; TMP and CCS pulps with 5% and 10% NaOH. Soaking in NaOH took place for 3 hours at 50-60 °C. TMP pulps were made from fibre that had been soaked in water overnight. Refining occurred at 16-18% s.c. after steaming at 69 kPa for 1 minute. The bark pulp (hb12, Appendix V.1a) used for bleaching was not presteamed and was refined at 12% s.c.

In addition, a low consistency 5% NaOH CCS pulp was prepared by refining at 2.2% s.c., in an attempt to reduce fibre tangling and subsequent sheet formation problems identified at the higher consistency. It was hoped that at a lower consistency, the fibre length would be reduced on passing through the refiner. A similar result was also sought by using a finer (2.5 mm) sieve in the Wiley mill.

Pulps from the low consistency experiments did not have latency removed before sheetmaking. Other bark fibre pulps needed to have latency removed to untangle the pulp fibres.

The drainage times of some of the bark pulps were measured.

Whole stem pulping trials:

To complete the pulping trials with hemp, whole stem material was also pulped using the TMP, 5% NaOH CCS and 10% NaOH CCS processes. The fibre was soaked in NaOH for 3 hours at 60 °C and steamed for one minute at 69 kPa, prior to refining at 11-13% s.c.

TMP was made after soaking the fibre in water overnight at 40 °C. The fibre was steamed for 1 minute at 69 kPa, then refined at 20% s.c.

Bleaching trials:

Samples of core pulps made with 5.2% NaOH (hc5/1, Appendix V.1b); bark pulps made with 12.8% and 13.3% NaOH (hb7/2 and hb12, Appendix V.1a); and whole stem pulps with 5% NaOH (bc3/2, Appendix V.1b) were bleached with various mixtures of hydrogen peroxide and sodium hydroxide, using 2% sodium silicate at 80 °C and 15% s.c. for 2 hours.

The optimum bleaching conditions for brightness were used to bleach additional pulp for strength evaluations.

V.2.2 Flax pulping trials:

Preparation:

Straw of the fibre flax cultivar Ariane was partially dew retted in the field for a period of five weeks in late summer/early autumn. The straw was then cut, decorticated and separated into the core and bark fractions using the same process described above for hemp. The water separation method was less successful than for hemp, resulting in a higher percentage of core contamination in the bark fraction. This was attributed to insufficient retting of the straw prior to processing.

Pulping trials:

The methods which gave the optimum results for the pulping of hemp formed the basis of the trials conducted with flax. This centred on the assumption that the pulping behaviour of flax would resemble that of hemp. This assumption was based on the reported similarities in the fibre properties of hemp and flax (McGovern *et al.* 1987) and the fact that their pulps are used interchangeably in the manufacture of specialty grades of paper (Wong & Chiu 1995).

Cold caustic soda pulps were made from core, bark and whole stem material presoaked with NaOH on a basis of 9.1%, 6.1% and 7.8% of oven dry fibre weight, respectively. The percentage of solids in the pretreatments was 20% for the bark fraction and whole stem and 15% for the core fraction. The presoaking was conducted in a water bath for approximately 3 hours at 60 °C. The whole stem mixture was then diluted to 15% s.c., the core fraction to 13.7% s.c., and the bark fraction to 16.5% s.c. They were then refined to varying degrees to produce pulps with a range of freeness values. Mixtures were not pre-steamed prior to refining, so as to maintain a better colour.

V.2.3 Pulp data for comparison:

Table V.1: Properties of softwood kraft, eucalypt CCS and pine TMP, May - June 1996; ANM Boyer. Properties based on conditioned basis weight.

Property	TMP Pine	CCS Eucalypt	Kraft
Freeness (CSF)	116	109	566
Bulk (cm^3/g)	2.50	1.68	1.58
Tear Index ($mN.m^2/g$)	7.33	4.34	19.34
Tensile Index (Nm.g)	36.52	52.19	44.81
Scatter. Coeff. (cm^2/g)	481	416	293

Table V.1 lists mill data for key kraft, CCS and TMP pulp properties averaged over a two month period (May - June 1996). These data were used for comparisons with the laboratory hemp and flax pulps. Data from the laboratory refining of kraft (Banham *et al.* 1994) were also used in graphical comparisons with bark pulp data.

V.3 Results:

The properties of all pulps described in this section are included as appendices to this report. Pulp properties are listed in Appendix V.1 and bleaching results in Appendix V.2.

V.3.1 Core pulping:

Hemp core fibre length:

Average fibre lengths for peracetic acid digests of both uncut core and Wiley mill processed samples were 0.47 mm compared with lengths of up to 0.58 mm for the refined core fibres. It is possible that parenchyma material which becomes fines material upon pulping, contributed to the apparent shorter fibre length measured in the digested material (chemical pulp), as the FS200 does not differentiate between different cell types.

Strength properties:

Hemp:

The key strength properties (tear and tensile strength) for the hemp TMP core pulps were poor relative to hemp core CCS and eucalypt CCS pulps (Figures V.2 and V.3). Additional refining to produce lower freeness pulps resulted in an increase in tensile strength. Pulps of similar quality have previously been observed with eucalypt TMP pulps (P. Banham, ANM internal memorandum 1991).

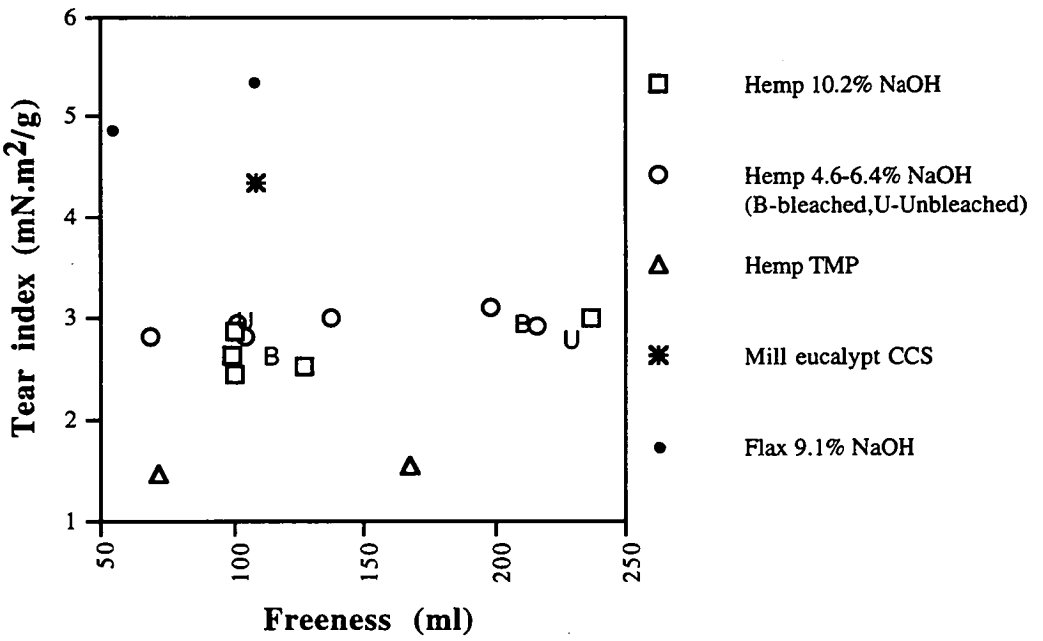


Figure V.2: Tear index versus freeness plot for all core pulps.

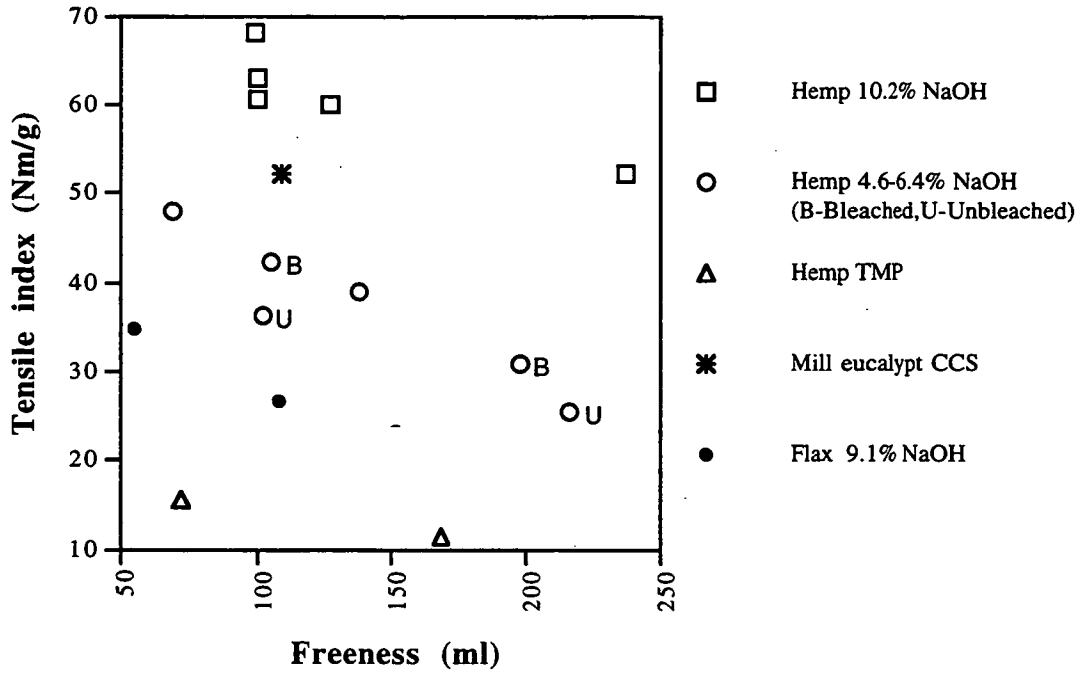


Figure V.3: Tensile index versus freeness plot for all core pulps.

Treatment with 5% NaOH resulted in substantial increases in pulp strength properties, although tear and tensile indices were still substantially less than eucalypt CCS pulp at equivalent freeness values. Additional refining brought about increases in tensile index and a decrease in tear index.

Treatment with 10% NaOH had the effect of substantially increasing tensile index up to a value approximately 10 Nm/g greater than eucalypt CCS. However, tear index remained approximately 1.5 mN.m^2/g less than that of eucalypt CCS pulp.

Flax:

The flax core CCS pulp had double the tear index of the equivalent hemp core CCS pulp and was approximately 1 mN.m^2/g higher than eucalypt CCS pulp. However, the tensile strength was almost half that of the hemp pulp and approximately 20 Nm/g less than for eucalypt CCS pulp (Figures V.2 and V.3).

Light scattering coefficient:

Hemp:

The light scattering coefficient of the hemp core TMP pulp was very high and superior to eucalypt groundwood pulp (Figure V.4). With 5% NaOH, the pulps were comparable to eucalypt CCS pulps. With 10% NaOH, the scattering coefficient was far less than that of eucalypt CCS.

Flax:

The light scattering coefficient values for the flax core CCS pulp were similar to those of the 10% NaOH CCS hemp core pulp (Figure V.4).

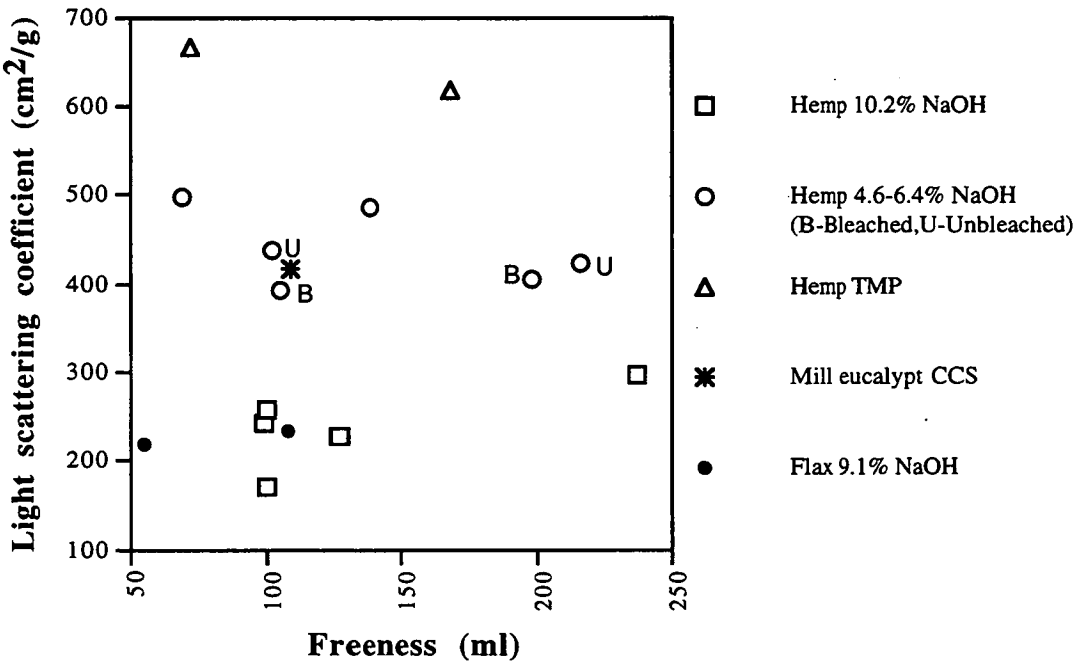


Figure V.4: Light scattering coefficient versus freeness plot for all core pulps.

Specific refining energy and handleability:

Hemp:

The refining energy for the core TMP pulps was very high compared to a eucalypt CCS pulp. The use of the sodium hydroxide treatments dramatically reduced the refining energy required to target a given freeness. With 10% NaOH, the specific refining energy to pulp to 100 ml CSF (Canadian Standard Freeness) in the laboratory was substantially less than for a eucalypt CCS pulp (Banham *et al.* 1996) (Figure V.5).

Although drainage times were not specifically measured, it was noted that the core pulps drained freely and did not exhibit slow drainage due to fragmented parenchyma.

Flax:

At equivalent freeness values, refining energy requirements for the flax core pulp were lower than both the eucalypt CCS and 10% NaOH CCS hemp core pulps (Figure V.5).

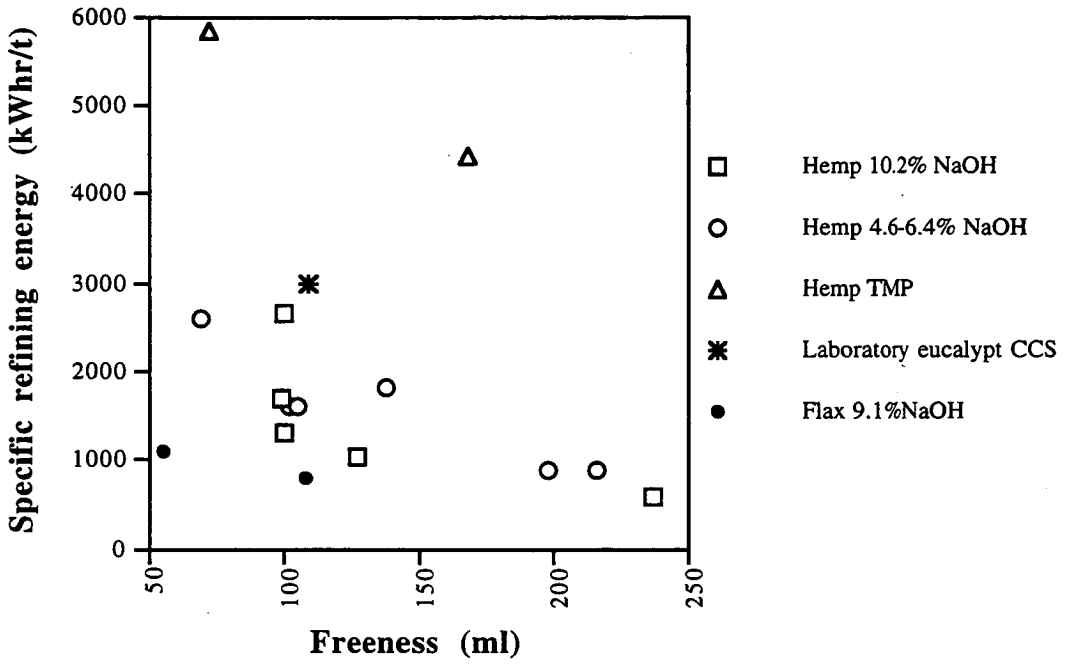


Figure V.5: Specific refining energy versus freeness plot for all core pulps.

Bleaching trials:

Hemp:

Bleaching with 2% H_2O_2 and 1.2% NaOH gave optimum brightness and colour attributes. The response to bleaching was dissimilar to that of eucalypt CCS pulp, giving an improvement of only 16.7 ISO brightness units with 2% H_2O_2 (c.f. 21 for eucalypt CCS) (P.Banham pers. comm. 1995). Use of 3% H_2O_2 gave no additional bleaching effect (Figure V.6).

Bleaching of the 5% NaOH CCS core pulps resulted in an increase in tensile index while tear index remained at similar levels (Figures V.2 & V.3). Presumably, fibre surface characteristics were influenced by bleaching in such a way as to promote

stronger inter-fibre bonding. However, gains in tensile index from bleaching of the 5% NaOH CCS pulp were insufficient to produce a pulp as strong as the 10% NaOH CCS pulp. That is, gains from bleaching were not as large as those from a higher concentration of caustic soda during pulping.

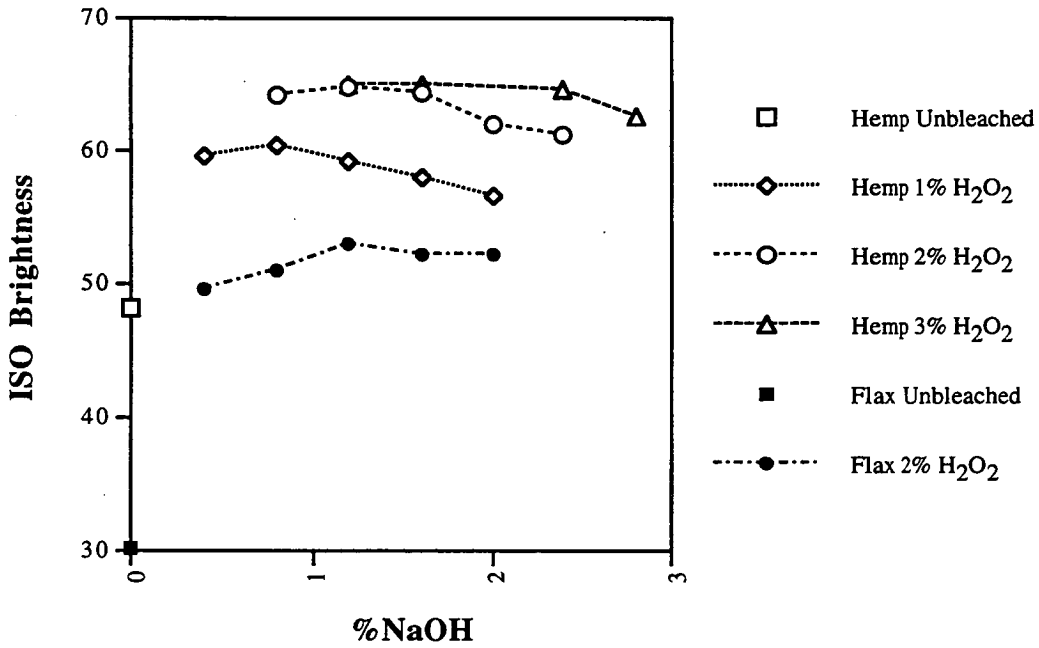


Figure V.6: Response of ISO brightness of hemp and flax core pulps to changes in the concentration of bleaching agents; H_2O_2 and NaOH.

Flax:

Bleaching with 2% peroxide and 1.2% sodium hydroxide gave optimum brightness and colour attributes for the flax core pulp (Figure V.6). Flax core pulps were generally less bright and not as white as hemp core pulps, as reflected in ISO brightness and L* colour index values, respectively. Furthermore, the pulps and handsheets were distinctly straw yellow in colour, as indicated by high values for the a* colour index.

The addition of blue dye would be required to counter the yellow colour of the pulp. This would have the effect of lowering brightness and the L* colour index. More extensive bleaching would be required in order to achieve brightness levels approaching those of normal newsprint (62-65 ISO brightness).

V.3.2 Bark pulping:

Strength properties:

Hemp:

The tear index values of the high consistency (ie refined at 16-18% s.c.) bark pulps were very large (Figure V.7). TMP pulps were close to 30 mN.m²/g at 434 ml CSF. The treatment of the fibre with sodium hydroxide improved the tear index further. The tear index of CCS pulps increased with refining up to a maximum value of between 33 and 38 mN.m²/g at approximately 350 to 450 ml CSF and then declined rapidly. The use of 10% NaOH did not improve tear strength compared with 5% NaOH.

At freeness values of about 400 ml CSF, the low consistency (ie refined at 2.2% s.c.) CCS pulps had much lower tear indices compared with the high consistency refined pulps. However, at lower freeness values, low consistency refining caused the tear index to increase to such an extent that it exceeded the high consistency tear index.

At comparable freeness values, the TMP and high consistency hemp bark CCS pulps had superior tear indices to softwood kraft pulp.

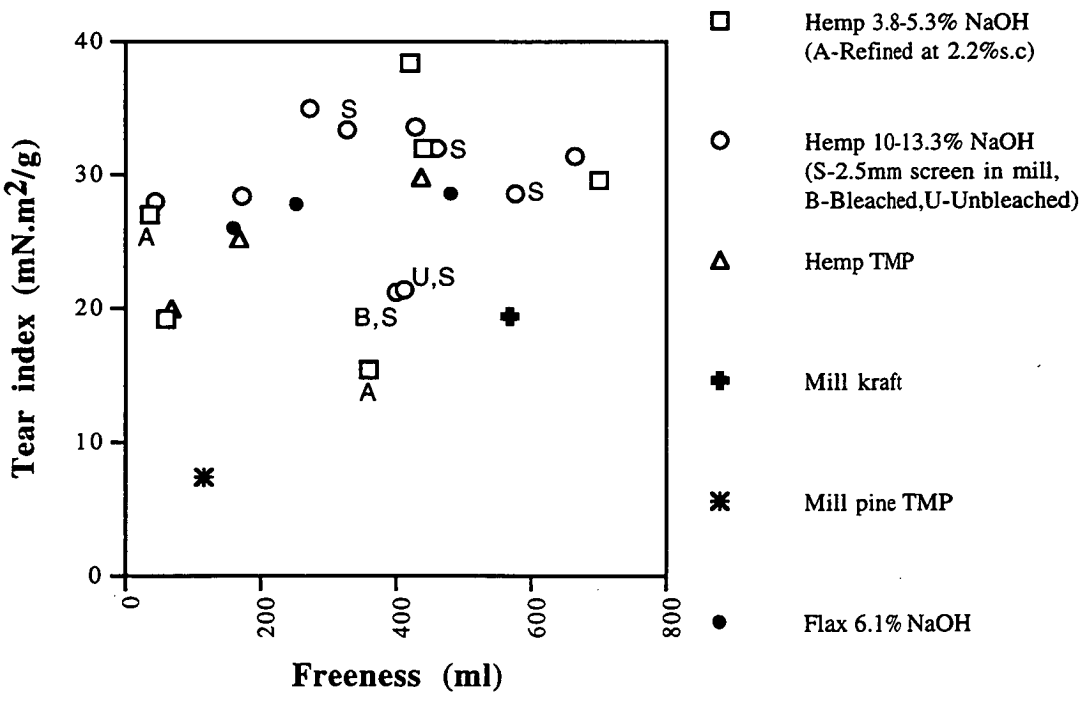


Figure V.7: Tear index versus freeness plot for all bark pulps.

Although the tear index of the bark pulps was superlative, the formation of the sheets was very poor. The fibre flocculated strongly during the sheet making process, exhibiting a strong tendency to form long clumps and strings as the fibres entangled each other. The low consistency refining experiments were an attempt to induce fibre cutting to improve formation and sacrifice some tear index. Visually, this did not succeed in improving formation, so in another experiment, a smaller screen was used in the Wiley mill to cut the fibre to a smaller length prior to pulping. Fibre length reduction achieved via this method appears to have had little effect, as the tear indices of the bark pulps were as good as in previous efforts without any substantial improvement in formation. In another experiment with the same aim, some of the -1.18 mm screen fraction was added to the +1.18 mm bark fibre prior to pulping. The tear index of the resultant mixture was substantially reduced to 21 mN.m^2/g and formation was much improved, although the fibre still had a tendency to tangle.

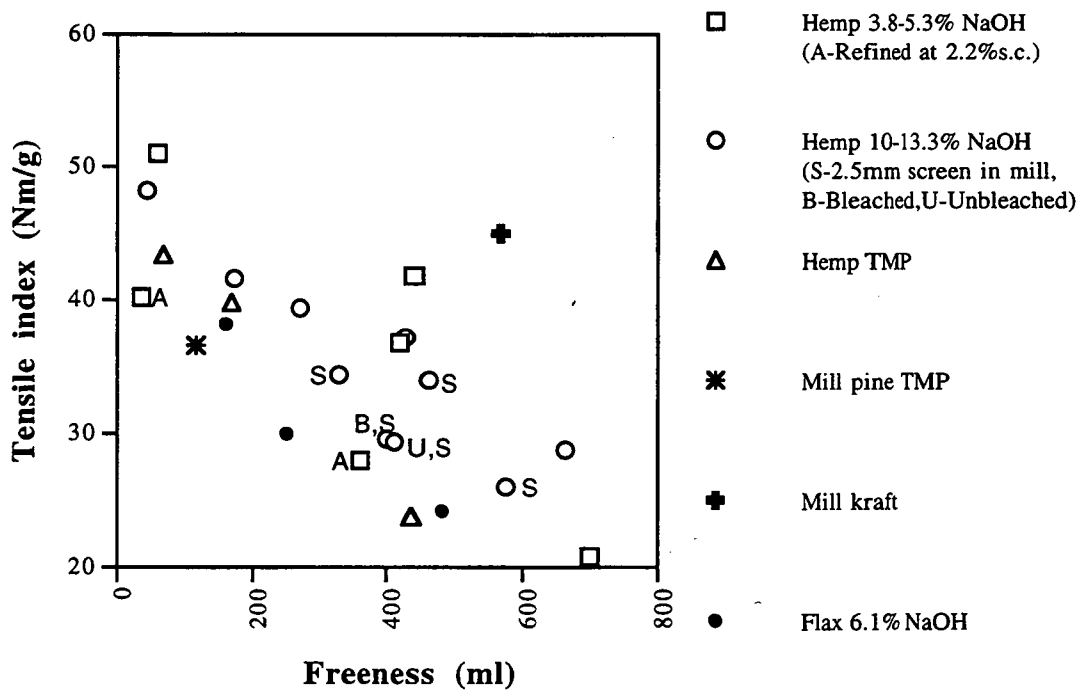


Figure V.8: Tensile index versus freeness plot for all bark pulps.

Tensile index increased with additional refining (and consequent reduction in freeness) across all pulping processes (Figure V.8). The high consistency 5% NaOH CCS and 10% NaOH CCS pulps had larger values of tensile index than the TMP treatments, especially at higher freeness values. Lowering the refining

consistency to 2.2% appeared to have a detrimental effect on tensile index. Both the addition of some of the -1.18 mm fraction and the use of a small screen in the Wiley mill appeared to reduce the tensile index of the bark pulps.

Tensile indices equivalent to those of kraft pulps were only achieved at very low freeness values (<70 ml CSF) for the two high consistency CCS pulps. At these freeness values, the pulps were (very) slow draining. At freeness values equivalent to those of the mill processed softwood kraft pulp, bark tensile strength was poor, despite the use of up to 12.8% NaOH. That is to say, tensile index values equivalent to mill kraft were achieved with hemp bark CCS pulps, but with a major tradeoff in terms of pulp drainage times and potentially in reduced mill production rates.

Flax:

The tear indices of the flax bark pulps were also high relative to kraft pulp. Tensile strength was substantially less than kraft and slightly less than hemp at equivalent freeness values (Figures V.7 & V.8).

Light scattering coefficient:

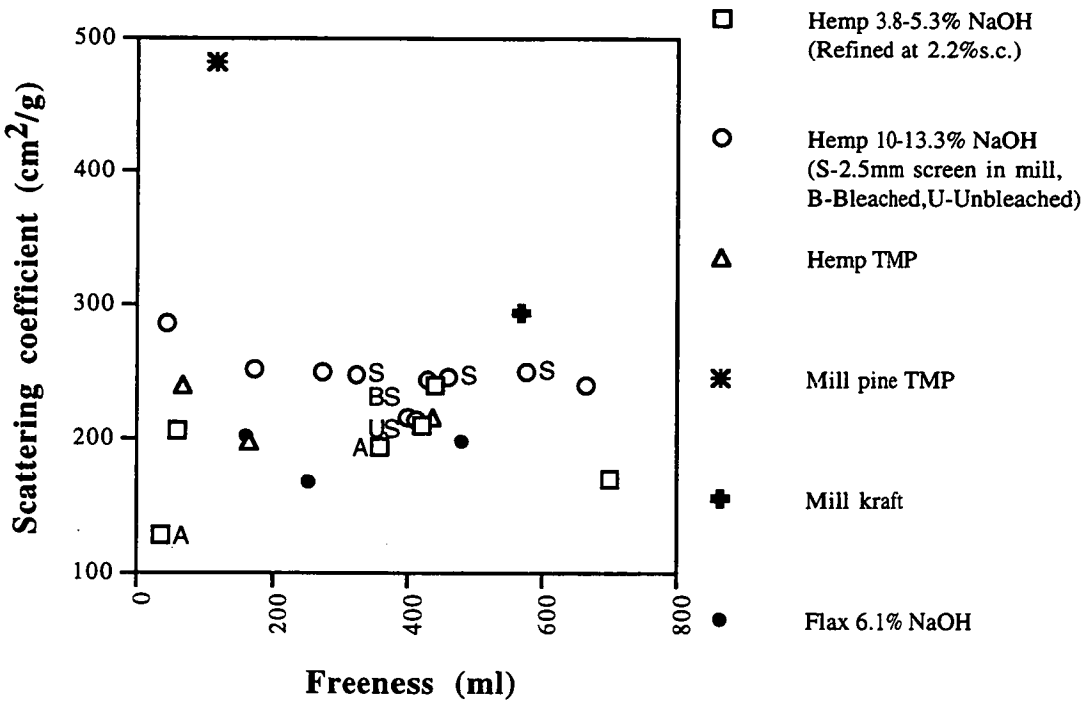


Figure V.9: Light scattering coefficient versus freeness plot for all bark pulps.

Light scattering coefficient values remained relatively constant and low across the various chemical and refining treatments (Figure V.9). Low consistency refining of hemp bark CCS reduced the scattering coefficient even further. At equivalent freeness values, the coefficients for the hemp and flax bark pulps were generally lower than those of softwood kraft pulp.

Specific refining energy and handleability:

Hemp:

Pulping of the bark fraction required very low energy inputs. Between 500-700 kWhr/t was required to refine the pulps to 400 to 450 ml CSF (Figure V.10).

The material handled well in the refiner, providing the consistency did not exceed 16-18% s.c. The pulp was readily burnt at higher values.

The ease of pulping the bark fibres was seen in the initial trials with the Lampen mill. When the different fractions from the sieving of the Wiley mill fibre were pulped, 35 minutes processing was all that was required to make the pulp comparable in strength properties to the refiner bark pulps.

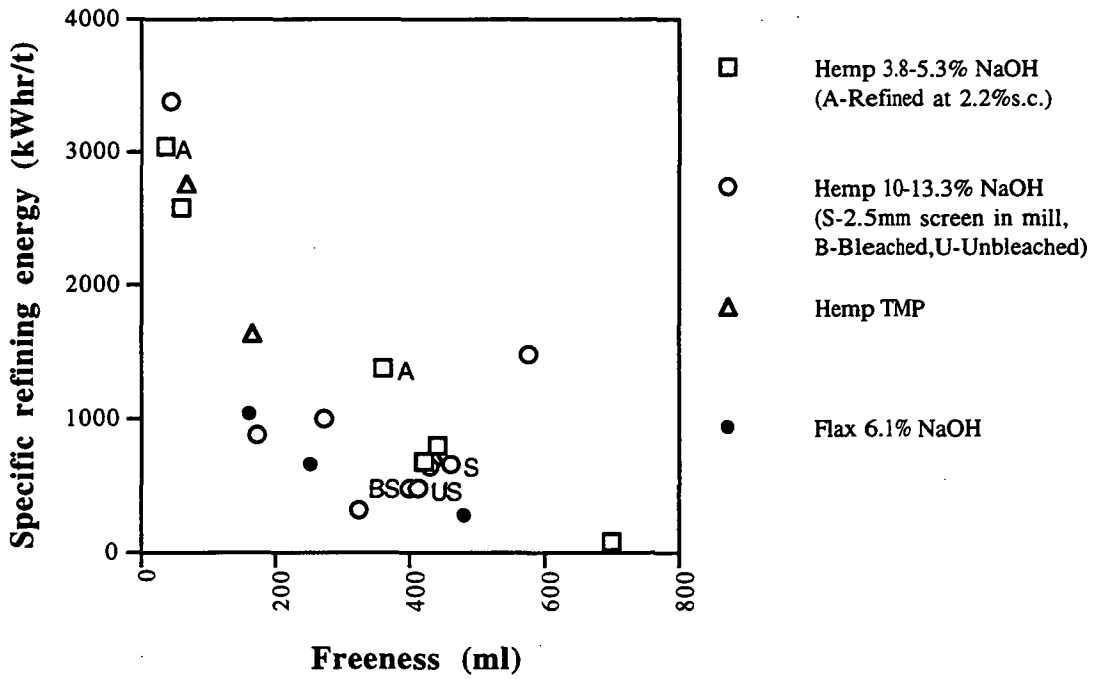


Figure V.10: Specific refining energy versus freeness plot for all bark pulps.

When refined, the bark pulps were very tangled. The latency removal process was successful in detangling the fibre from the refiner but many of the pulps later tangled in the sheet making stage and tended to form tangled lumps on projecting surfaces. Fibre length analysis of the Lampen mill bark fibre samples revealed a broad distribution in length with fibres up to 6 mm long. This probably contributed to the tendency for the fibres to tangle and clump together in many of the bark pulps.

When attempts were made to screen the bark pulps through a coarse wire mesh (1.18 mm) in order to remove hemp core contaminants, the fibre was found to coat the mesh and block the screen. This behaviour points to potential problems with newsprint screening systems. The fibre is likely to drape over the bars of the screen basket and cause blinding. A specially designed basket would be required to handle this kind of fibre.

Flax:

Flax bark fibres also tended to tangle and block screens during the pulping process. The refining energy was similar to the hemp bark CCS pulps.

Bleaching trials:

Hemp:

Bark pulps responded better to bleaching than core pulps (Figure V.11 & V.6). An average gain of 25.8 units of brightness was obtained with 2% H_2O_2. Additional hydrogen peroxide gave only a small improvement in brightness.

Bleaching the bark pulp showed no significant effect upon tensile index or light scattering coefficient (Figures V.8 & V.9). However, surface roughness and porosity appeared to increase upon bleaching (Appendix V.1a).

Flax:

The unbleached brightness of the flax bark pulp was approximately 18 ISO brightness units higher than the unbleached flax core pulp (Figure V.11). The maximum brightness achieved from bleaching was comparable to that of the bleached hemp bark pulps.

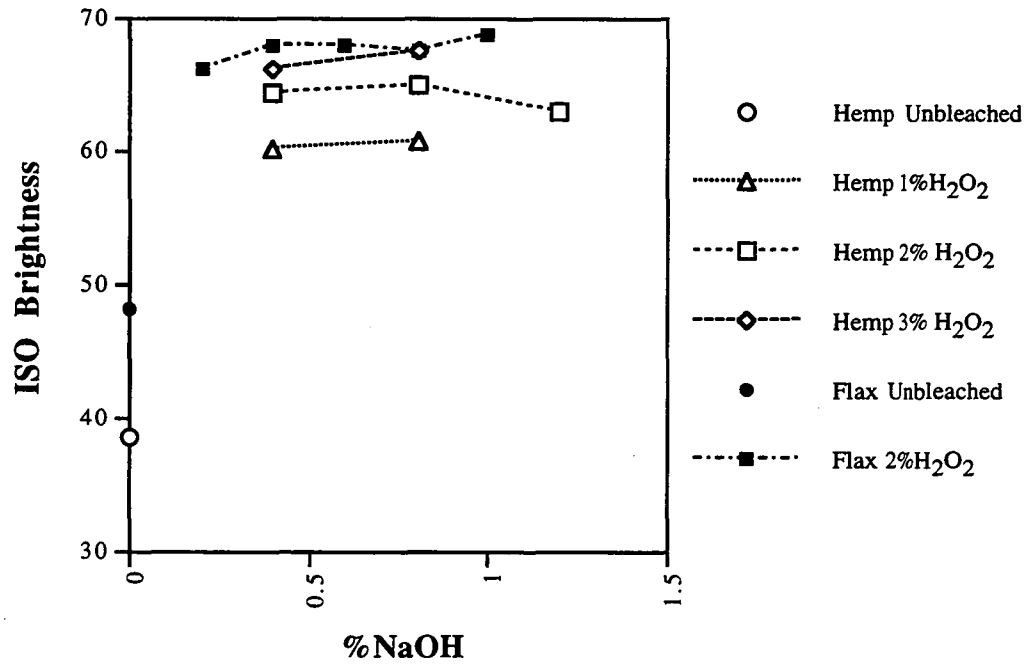


Figure V.11: Response of bark pulp ISO brightness to changes in the concentration of bleaching agents; H_2O_2 and NaOH.

V.3.3 Whole stem pulping:

The hemp TMP pulp was full of pieces of core material and was very rough in appearance. Cleaning of the whole stem pulp proved difficult due to the holding effect of the bark fibre. It was only with 10.1% NaOH that the core was largely broken down during pulping and was not considered as a major contaminant.

At equivalent freeness values, the properties of the whole stem pulps of both hemp and flax were generally between those of the separated core and bark pulps produced by the same process. The pulp properties were closer to those of the core than the bark pulps, reflecting the greater proportion of core in the whole stem mix. Most significant was the large reduction in the tear strength of the TMP and CCS bark pulps upon the addition of the core fraction (Figures V.7 & V.12).

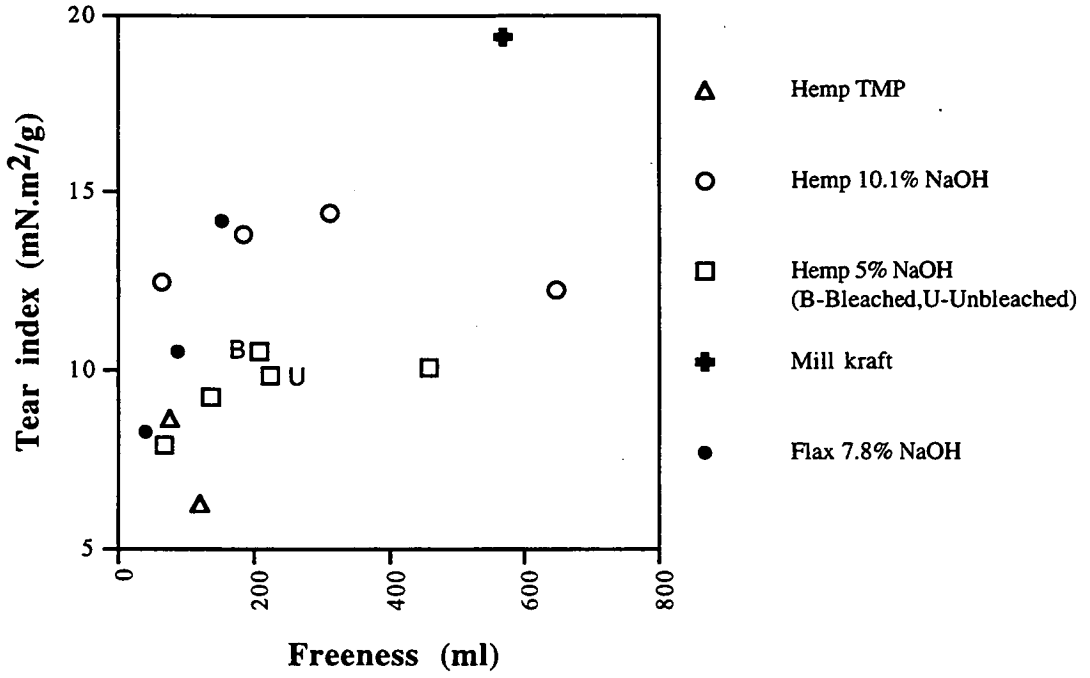


Figure V.12: Tear index versus freeness plot for all whole stem pulps.

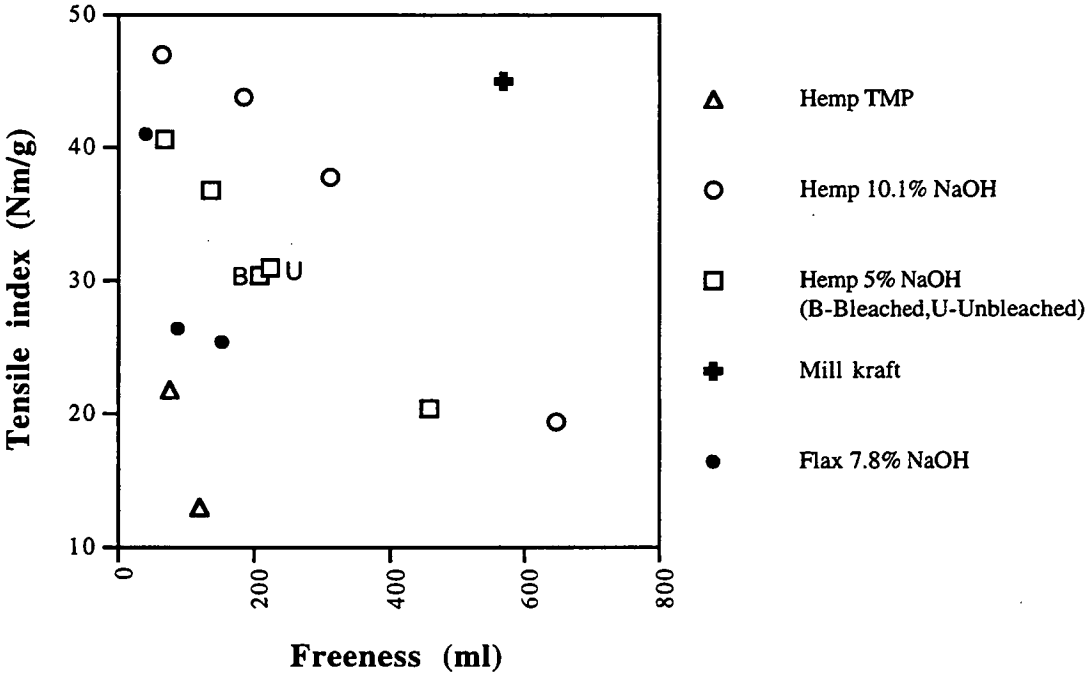


Figure V.13: Tensile index versus freeness plot for all whole stem pulps.

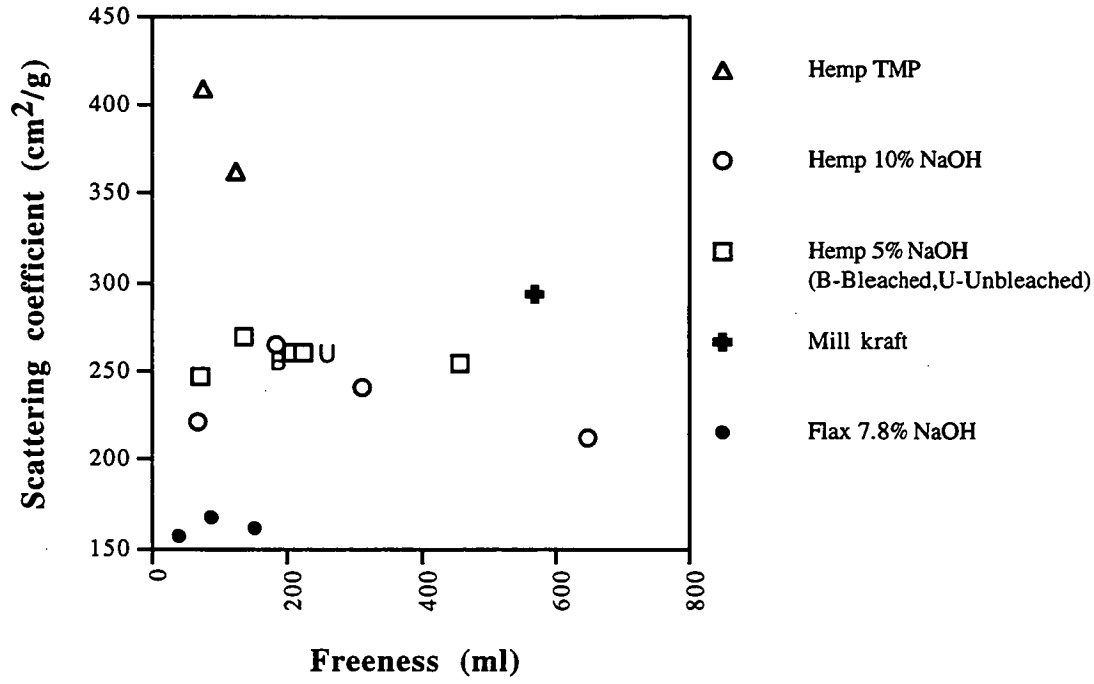


Figure V.14: Light scattering coefficient versus freeness plot for all whole stem pulps.

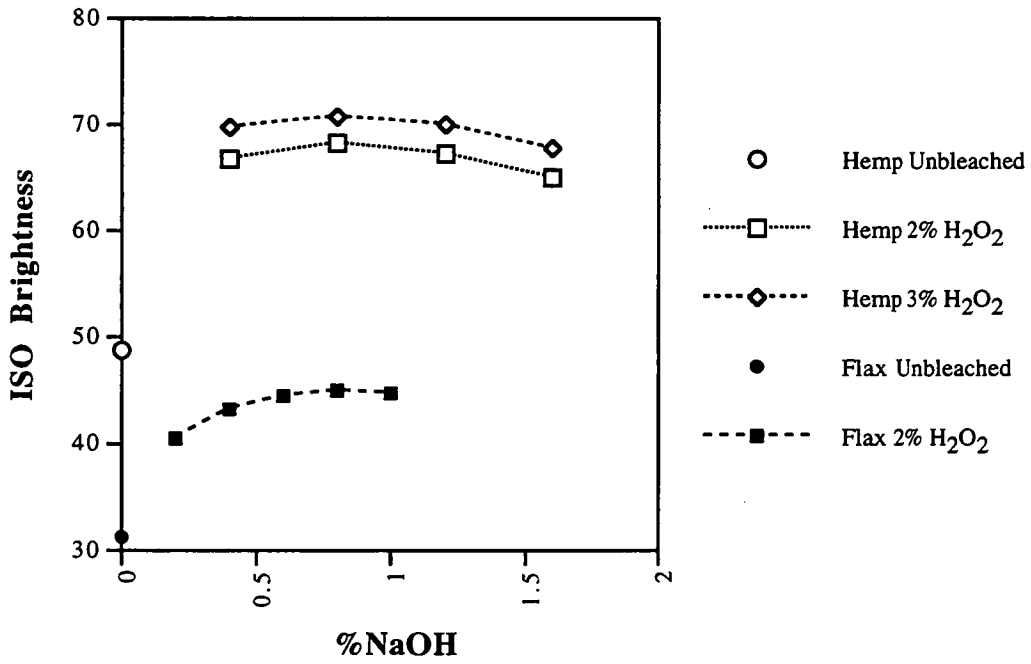


Figure V.15: Response of whole stem pulp ISO brightness to changes in the concentration of bleaching agents; H_2O_2 and NaOH.

The light scattering coefficients of the CCS hemp pulps were low and similar to softwood kraft (Figure V.14). Whole stem flax pulps had even lower scattering

coefficients, indicative of the low values recorded for partitioned core and bark pulps.

The brightness of flax whole stem pulp was less than for the flax bark and core pulps and poor in comparison with hemp whole stem pulp. This anomaly may have been caused by higher temperatures in the refiner when pulping the flax whole stem material.

V.4 Discussion:

The behaviour of the hemp core pulps was analogous to that of eucalypt except that properties developed more with chemical addition. These pulps were typically of low tear index and high tensile index. Tensile index tended to increase with the use of a higher concentration of sodium hydroxide. Generally, except for the poor tear index and scattering coefficient, the 10% NaOH CCS hemp core pulp is similar to the eucalypt CCS pulp currently used in the operation at ANM Ltd.

The flax CCS core pulps had superior tear strength but had lower tensile strength, lower brightness and were very yellow in color compared with the equivalent CCS hemp pulp and mill eucalypt CCS.

Although it would be possible to feed hemp and flax core into the existing CCS plant at ANM, the proportion would need to be watched carefully so as not to adversely affect the strength and optical properties of the total blend. At present, there is no demand for additional short fibred pulp, and indeed there is speculation regarding a shift toward newsprint production from pine and recycled fibre.

The properties and behaviour of hemp and flax CCS bark pulps were similar and could potentially be blended or used interchangeably. The bark fibres of hemp and flax are capable of forming paper of very high tear index but with lower tensile index (Figure V.16) and tensile energy absorption (TEA, Figure V.17) than would be desirable from a softwood kraft. The TEA, which is the amount of energy required to rupture bonds in the sheet of paper, is likely to be as important for sheet strength as the tensile index.

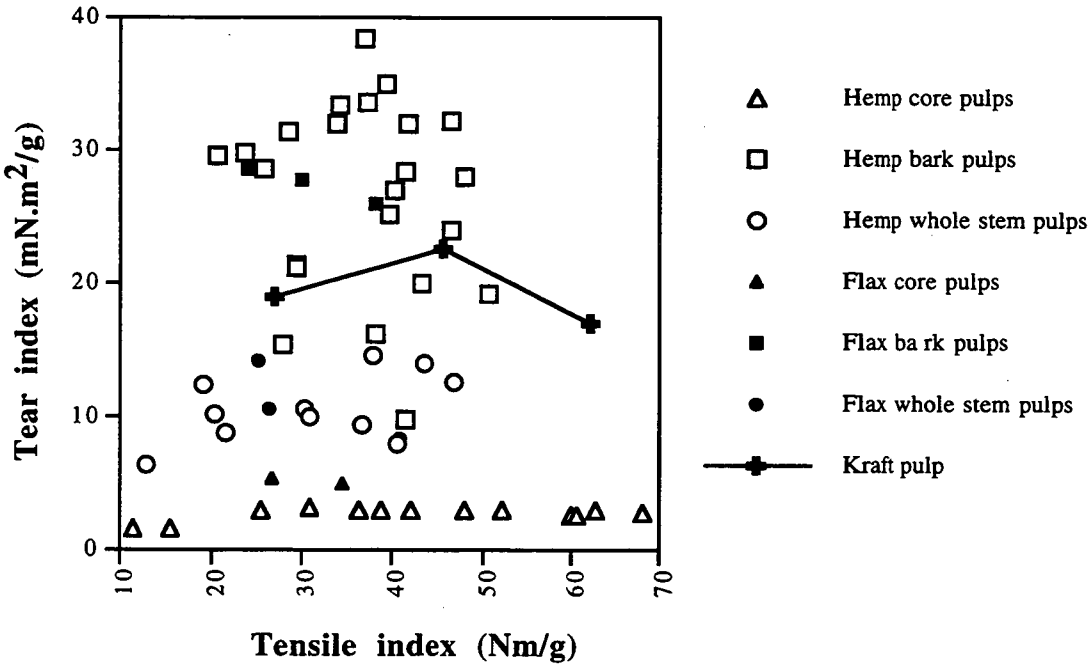


Figure V.16: Tear index versus tensile index plot for all hemp and flax pulps, and laboratory refiner results for kraft pulp (Banham *et al.* 1994) .

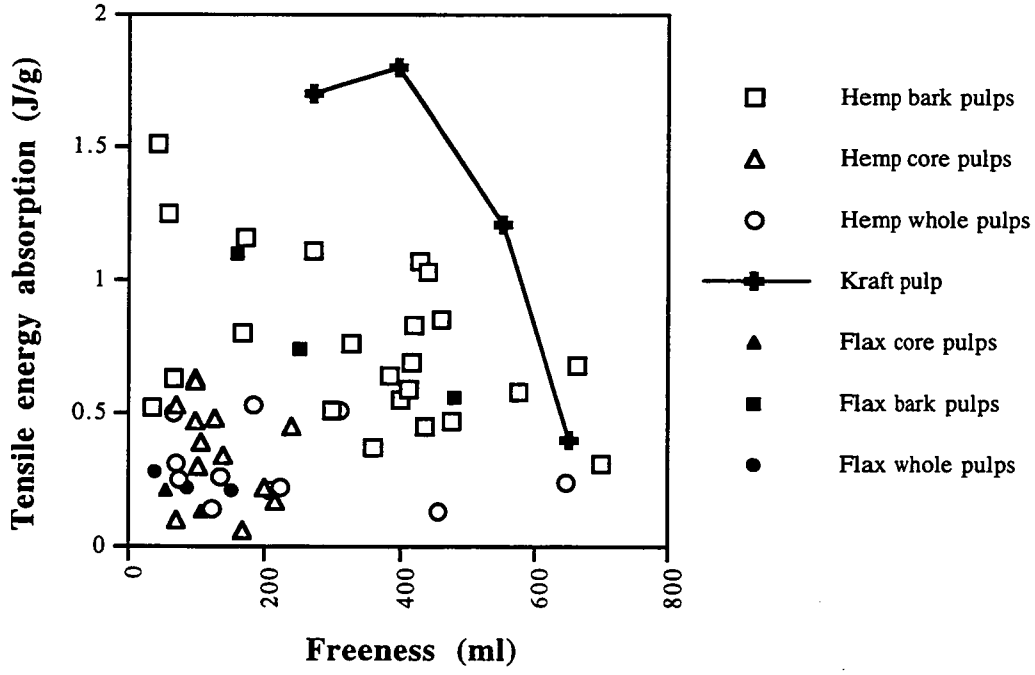


Figure V.17: Tensile energy absorption versus freeness plot for all hemp and flax pulps, and laboratory refiner results for kraft pulp (Banham *et al.* 1994).

Van Roekel *et al.* (1995) report similar findings for tear and tensile strength properties of a peroxide bleached, alkaline pre-treated extruder pulp of hemp bark. They concluded that such a pulp might be considered to replace kraft, with the

acceptance of a reduction in tensile strength. Hague and Goodwin (1996) also report on the relatively high tear and low tensile indices of hemp and flax chemical and semi-chemical pulps.

The shortfall in tensile strength might be overcome by using a higher proportion of bark pulp (in comparison with kraft) in the newsprint blend (P.Banham pers. comm. 1997). This however, would increase the relative cost of hemp and flax bark pulp. Another approach might be to develop new cultivars with fibre traits which promote tensile strength. Key determinants are individual fibre strength and bond strength. Bond strength is a combination of bond strength per unit area and more importantly, total bonded area. Bonded area is a function of fibre dimensions, particularly lumen perimeter (McKenzie 1994). Significant diversity in fibre strength and strain (% elongation) has been found to exist between flax genotypes (Scheer-Triebel 1993). Diversity was also found in the synchronisation of fibre and seed maturity. This is suggested as a further selection criterion for dual purpose flax breeding, as fibre strength can deteriorate between fibre and seed maturity. Assessment of genotypic diversity and crop management influences on the key fibre strengh properties of *Cannabis* may reveal a similar potential for improvement in tensile strength through breeding and/or improved cultural practices.

The bark CCS pulps had low light scattering coefficient values. Increasing the proportion of pine TMP (high light scattering coefficient) in the pulp blend could potentially offset the reduction in scattering coefficient associated with kraft replacement.

The energy required for refining bark CCS pulps was substantially lower than that which is required for pulping wood.

The tendency of the bark fibre to tangle and block screens, highlights the need for more accurate and uniform fibre cutting. Van Roekel *et al.* (1995) report that the extruder method of pulping satisfactorily cuts long fibres to a length preventing tangling. This is achieved without greatly reducing the dewatering rate of the pulp and retaining sufficient strength to allow use as a reinforcing pulp.

Whole stem pulp properties were generally intermediate to those of separate core

and bark fibre pulps but weighted more toward the core fibre properties. The tear index, tensile index and TEA of the whole stem pulps were not as high as softwood kraft.

Section VI: Economics of hemp and flax production for use as a reinforcing agent in the Tasmanian newsprint industry.

VI.1 Introduction:

The purpose of this part of the project was to investigate the economics of hemp and flax production in Tasmania and to compare the likely returns with existing crop options.

The economic analysis presented here is based on an approach employed by the Tasmanian Department of Primary Industry and Fisheries to assess the potential of new crops. Budgets were prepared from the likely yields, costs and prices for crop production in order to calculate the gross margin and enterprise contribution for each crop. The gross margin is a measure of gross income less variable costs and is a useful comparative tool for assessing which crop would contribute the most to a farm's cash flow. The enterprise contribution is the gross margin less allocated overhead costs and gives an indication of the ability of the crop to 'pay its way', ie the extent to which the returns from the crop can cover both fixed and variable costs associated with its production (Anonymous 1994).

Given that the crop budgets represent just one set of conditions, a series of sensitivity analyses were conducted to assess the response of the gross margin to fluctuations in the value of key selected parameters.

VI.2 Budget assumptions and structure:

The following assumptions were made in the preparation of the production budgets.

1) The market scenario employed in the preparation of the budgets was based on the sale of the stem bark fraction to ANM Ltd. for use as a reinforcing agent in newsprint manufacture. This is based on the conclusion from the pulping trials (Section V) that there is no potential at present for using the core fraction or whole stem in newsprint manufacture. It was assumed that flax would be grown as a dual purpose crop, with the sale of Linola seed contributing to the gross margin from this

crop.

2) The cost of flax seed for resowing was based on the cost of Linola seed (Seedex, pers. comm. 1996).

3) Fitzgerald (1995) quotes hemp seed prices in Europe of between AUS$1/kg and $5/kg. Selkirk (1996) reports a price of $2.50/kg for Kompolti and $6.10/kg for seed of French cultivars. Small samples of Ukrainian seed imported for the 1994-95 trials cost approximately $6.50/kg (including freight). Seed imported from the United Kingdom cost $10/kg. In the long term, larger scale cultivation requiring larger volumes of seed would inevitably lead to local seed production and a significant reduction in seed cost. A hemp seed price of $5/kg was used in the preparation of the hemp budget.

4) The optimum seeding rate for hemp was taken as 20 kg/ha (approximately 100 plants/m^2). A rate of 100 kg/ha was adopted for dual purpose flax, representing a compromise between maximising stem yield and minimising the risk of lodging.

5) It was assumed that optimum yields for both crops would require irrigation through late spring and summer. A total of 120 mm of irrigation was used for flax and 240 mm for hemp. An economic comparison between irrigated and rainfed flax cropping is considered in the following discussion.

6) Land preparation for both crops was assumed to consist of one mouldboard ploughing followed by a roterra cultivation.

7) Fertiliser application rates and methods were based on literature recommendations, experience from the the field trials discussed in Sections II and III, and existing agricultural practices in Tasmania. For hemp, an NPK blend was band placed at sowing followed by a post emergent topdressing of a nitrogen fertiliser. In the case of flax, an NPK blend was pre-drilled prior to sowing.

8) Hemp was assumed to not require herbicides. Herbicide rates for flax were taken from Green *et al.* (1994).

9) Pesticide requirements were set at $30/ha for each crop.

10) Variable costs for tractor and plant activities were based on estimates of the expected time for each cultural operation and an hourly rate that takes into account fuel and maintenance costs.

11) The contracting rates used for harvesting operations were based on 1996 commercial rates in Tasmania.

12) Allocated overhead costs are those which are unaffected by the enterprise mix on the farm, such as machinery ownership and permanent labour costs. They are allocated to each crop based on the estimated time spent on the crop or, in the case of irrigation equipment, on the amount of water applied. A detailed description of the derivation of overhead cost parameters is given by Anonymous (1995).

13) The security figure in the hemp budgets was based on the cost of security to the Tasmanian poppy industry in 1995. It takes into account the cost of the police task force ($250 000 per annum) and the equivalent of one field officer ($50 000 per annum). The patrol area was assumed to be 8000 ha. Administration expenses were not included in the security costings.

14) It was assumed that the hemp crop would be windrowed at flowering and allowed to dry (turned once) until the moisture content was ~12-15%. The stem would then be decorticated using a field hemp breaker, as described by Graham (1995) and the bark fibre subsequently baled in large round bales. The same straw harvest costs were assumed for flax with an additional cost for heading of the seed.

15) Whilst the main budget assumes that there is no market for the core, it is recognised that the core may have potential in non-paper applications (Section VII). The effect of core sale on the gross margin is considered in a separate sensitivity analysis.

16) Yield estimates were based on the results of the field trials reported in Sections II and III. Average stem (air dry) and seed yields of 7 t/ha and 1.7 t/ha are achievable from irrigated, dual purpose flax crops. Rainfed crops might be

expected to yield 5 t/ha of stem and 1 t/ha of seed. Similarly, average stem yields of 10 t/ha are achievable from an irrigated hemp crop. The effect of stem yield on gross margin was considered in a sensitivity analysis.

17) References to the market price of decorticated hemp bark fibre were found to vary considerably. Whole stem prices were more consistent at between $150 and $200/t (Fitzgerald 1995, Selkirk 1996). The bark fibre price used in the main budgets ($650/air dry tonne) was based on a whole stem price of $200/t, a bark fibre percentage of 35%, an 85% efficient, field based decortication process (ie 30% yield from stem), and a cost of $53 to separate, bale and cart (150 km) one tonne of bark fibre (Graham 1995). Given the uncertainty regarding price, a sensitivity analysis was prepared to examine the reponse of gross margin to fluctuations in this parameter. For the purposes of the model budgets, the price of flax fibre was assumed to be the same as for hemp.

18) The price paid for Linola seed equates to the value of seed sold for oil extraction (Seedex, pers. comm. 1996). This was assumed to be a farm gate price.

VI.3 Alternative crop gross margins:

Table VI.1 lists gross margin figures for a number of selected crops currently grown in Tasmania. Similar figures to those listed for northern Tasmania (Anonymous 1994) also apply for the south east, east coast and the midlands regions of Tasmania.

Table VI.1: Gross margins for selected crops grown in northern Tasmania (a) (Anonymous 1994) and north west Tasmania (b) (Anonymous 1995).

a) Northern Tasmania		b) North West Tasmania	
Crop	Gross Margin ($/ha)	Crop	Gross Margin ($/ha)
Oats	26-130	Barley	326
Barley	227-264	Wheat	389
Wheat	284-333	Green peas	1144
Lupins	438	Green beans	1252
Green peas	998	Sweet corn	1537
Lucerne	1463	Onions	4086
Poppies	1229-2260	Potatoes	4953-5952

Table VI.2: Crop budget for hemp bark fibre production and sale to the newsprint industry as a reinforcing agent.

Gross Income:			**$/ha**
Air dry stem yield	10 t/ha		
% Bark	30 %		
Bark yield	3 t/ha		
Bark price & return	650 $/t		1950
Core yield	7 t/ha		
Core price & return	0 $/t		0
Total gross income			**1950**
Variable costs:			
Materials			
Seed	20 kg/ha @	5 $/kg	100
Fertiliser: 9:13:17	300 kg/ha @	418 $/t	125
Fertiliser: Urea	100 kg/ha @	425 $/t	42
Pesticides			30
Tractor & Plant			
Land preparation	5.3 hrs/ha @	11.64 $/hr	62
Drilling	1 hrs/ha @	11.64 $/hr	12
Fertiliser	0.6 hrs/ha @	8.35 $/hr	5
Pest control	0.6 hrs/ha @	8.35 $/hr	5
Contract			
Windrowing		50 $/ha	50
Turning	0.5 hrs/ha @	40 $/hr	20
Decortication/baling/cartage (150km)	3 t bark/ha	53 $/t	159
Irrigation	240 mm @	23 $/25mm	221
Security		40 $/ha	40
Total variable cost			**871**
Gross Margin			**1079**
Allocated overhead costs:			
Tractor & plant			
Land preparation	5.3 hrs/ha @	19.93 $/hr	106
Drilling	1 hrs/ha @	26.53 $/hr	27
Pest control	0.6 hrs/ha @	10.65 $/hr	6
Fertiliser-topdress	0.6 hrs/ha @	21.42 $/hr	13
Permanent labour			
Tractor operations	7.5 hrs/ha @	12.02 $/hr	90
Irrigation	4.5 hrs/ha @	12.02 $/hr	54
Irrigation	240 mm @	19.73 $/25mm	189
Total allocated costs			**485**
Enterprise contribution			**594**

Table VI.3: Crop budget for the production and sale of flax bark fibre and Linola seed.

Gross Income:			**$/ha**
Air dry stem yield	7 t/ha		
% Bark	30 %		
Bark yield	2.1 t/ha		
Bark price & return	650 $/t		1365
Core yield	4.9 t/ha		
Core price & return	0 $/t		0
Seed yield	1.7 t/ha		
Seed price & return	310 $/t		527
Total gross income			**1892**
Variable costs:			
Materials			
Seed	100 kg/ha @	1.25 $/kg	125
Fertiliser: 11:13:19	300 kg/ha @	422.00 $/t	127
Herbicides (Trifluralin)	1.4 L/ha @	7.30 $/L	10
Herbicides (Bromoxynil)	1.4 L/ha @	14.70 $/L	21
Pesticides			30
Tractor & Plant			
Land preparation	5.3 hrs/ha @	11.64 $/hr	62
Drilling	1 hrs/ha @	11.64 $/hr	12
Fertiliser	1 hrs/ha @	8.35 $/hr	8
Weed control (2 sprays)	1.2 hrs/ha @	8.35 $/hr	10
Pest control	0.6 hrs/ha @	8.35 $/hr	5
Contract			
Seed heading	0.5 hrs/ha @	200.00 $/hr	100
Windrowing		50.00 $/ha	50
Turning	0.5 hrs/ha @	40.00 $/hr	20
Decortication/baling/cartage (150km)	2.1 t bark/ha	53.00 $/t	111
Irrigation	120 mm @	23.00 $/25mm	110
Total variable cost			**801**
Gross Margin			**1091**
Allocated overhead costs:			
Tractor & plant			
Land preparation	5.3 hrs/ha @	19.93 $/hr	106
Drilling	1 hrs/ha @	26.53 $/hr	27
Pest control	0.6 hrs/ha @	10.65 $/hr	6
Weed control	1.2 hrs/ha @	10.65 $/hr	13
Fertiliser-predrilling	1 hrs/ha @	26.53 $/hr	27
Permanent labour			
Tractor operations	9.1 hrs/ha @	12.02 $/hr	109
Irrigation	3 hrs/ha @	12.02 $/hr	36
Irrigation	120 mm @	19.73 $/25mm	95
Total allocated costs			**418**
Enterprise contribution			**673**

VI.4 Budgets & sensitivity analyses:

The likely crop budgets for hemp and flax are shown in Tables VI.2 and VI.3 respectively. The response of the hemp gross margin to changes in stem yield and the price paid for the two stem fractions is shown in Table VI.4. The response of the gross margin of flax to seed price, bark fibre price and stem yield is shown in Table VI.5.

Table VI.4: Sensitivity of hemp gross margin to stem yield, bark fibre price (a) and core price (b). In (b), stem yield is 10 t/ha and the core price is a farm gate price.

a)

Stem yield (t/ha):	Bark fibre price ($/t): 250	350	450	550	650	750
7	-298	-88	122	332	542	752
8	-239	1	241	481	721	961
9	-180	90	360	630	900	1170
10	-121	179	479	779	1079	1379
11	-62	268	598	928	1258	1588
12	-3	357	717	1077	1437	1797
13	56	446	836	1226	1616	2006
14	115	535	955	1375	1795	2215
15	174	624	1074	1524	1974	2424

b)

Core price ($/t):	Bark fibre price ($/t): 250	350	450	550	650	750
0	-121	179	479	779	1079	1379
50	229	529	829	1129	1429	1729
100	579	879	1179	1479	1779	2079
150	929	1229	1529	1829	2129	2429
200	1279	1579	1879	2179	2479	2779

Table VI.5: Sensitivity of flax gross margin to stem yield and bark fibre price at seed yields of 0 t/ha (a), 1 t/ha (b) and 2 t/ha (c). Add $110 for rainfed margins (eg bracketted values in (b)).

a)

Stem yield (t/ha):	Bark fibre price ($/t): 250	350	450	550	650	750
3	-412	-322	-232	-142	-52	38
4	-353	-233	-113	7	127	247
5	-294	-144	6	156	306	456
6	-235	-55	125	305	485	665
7	-176	34	244	454	664	874
8	-117	123	363	603	843	1083
9	-58	212	482	752	1022	1292
10	1	301	601	901	1201	1501

b)

Stem yield (t/ha):	Bark fibre price ($/t): 250	350	450	550	650	750
3	-202	-112	-22	68	158	248
4	-143	-23	97	217	337	457
5	-84(26)	66(176)	216(326)	366(476)	516(626)	666(776)
6	-25	155	335	515	695	875
7	34	244	454	664	874	1084
8	93	333	573	813	1053	1293
9	152	422	692	962	1232	1502
10	211	511	811	1111	1411	1711

c)

Stem yield (t/ha):	Bark fibre price ($/t): 250	350	450	550	650	750
3	108	198	288	378	468	558
4	167	287	407	527	647	767
5	226	376	526	676	826	976
6	285	465	645	825	1005	1185
7	344	554	764	974	1184	1394
8	403	643	883	1123	1363	1603
9	462	732	1002	1272	1542	1812
10	521	821	1121	1421	1721	2021

VI.5 Discussion:

The attractiveness of these crops to farmers relies on the financial returns being comparable to existing crop options. In comparison with crops grown on better quality soils in the higher rainfall/irrigated areas of north west Tasmania, the gross margins compare favourably with alternative crop options (Tables VI.1, VI.2 & VI.3). It should be noted that transport costs from the north west of the state would be

approximately twice that used in the preparation of the budgets (150 km) shown in Tables VI.2 and VI.3. This would increase the cost of decortication, baling and cartage from $53/t to $70/t (Graham 1995). Taking this into account, the gross margins for hemp and flax grown in the north west would be similar and comparable with returns from green peas and broad beans (Anonymous 1995).

The lowest gross margins in the northwest cropping rotations are for wheat and malting barley at between $300 and $400/ha (Anonymous 1995). Assuming that all other parameter estimates are valid, the minimum price for hemp bark fibre that would give comparable returns to these cereal crops is approximately $400/t (Table VI.4a). The minimum price for dual purpose flax would be somewhat less at approximately $350/t. These cereal crops are primarily grown as a break crop in the rotation. Whilst of value in a similar role in the existing rotation, the substantial investment required for flax and especially hemp cultivation, suggest that their gross margins would need to be comparable with the higher returning crops (Table VI.1) in order to generate farmer interest.

Dual purpose flax would be potentially suited to the predominantly dryland cropping areas in the north, south east, east and midlands of Tasmania. Under dryland conditions, the gross margin from a dual purpose crop with average stem and seed yields of 5 t/ha and 1 t/ha respectively, would lie between lupins and green peas and be higher than most cereal crops. The lowest gross margin in this region is currently received from oats, at between $30/ha and $130/ha (Anonymous 1994). The minimum bark price to give comparable returns to this crop would be between about $250/t and $320/t (Table VI.5b). Comparable gross margins to barley (malting grade) and wheat would require a bark price of between $400/t and $450/t.

Table VI.5 clearly demonstrates that the sale of seed offers the potential to greatly enhance returns from flax. Assuming the validity of the estimated price of $310/t paid for seed, the gross margin from a dual purpose flax crop (Tables VI.5b and VI.5c) would be almost twice that of the fibre only crop (minus header costs) (Table VI.5a). The dual return from this crop may also provide a pricing advantage for Linola oil, thus enabling it to be more competitive against existing single purpose oilseed crops.

Similarly, the sale of the core fraction offers the potential to substantially improve the financial attractiveness of each crop (Table VI.4b). However, in the absence of a current local market, the core has value as a soil amendment only.

Section VII: General discussion.

VII.1 Introduction:

This final section brings together the main findings of the study for the purpose of addressing the key project questions outlined in the thesis introduction (Section I), namely:

1) What are the potential fibre yields from flax and hemp grown in Tasmania?.

2) How can genotypic and cultural factors be manipulated to produce these potential yields?.

3) Can a model be developed to simulate the growth and development and hence yield of hemp?.

4) Can the stem fibre of these crops be used to replace imported kraft pulp to make a satisfactory paper at a competitive price?.

VII.2 Production potential:

Flax:

The results from a flax cultivar trial showed that stem yields of selected European cultivars were superior to a number of older Australian cultivars, developed for the Australian flax industry during the mid 1900's. The superior performance of the European cultivars reflects the economic importance of flax over a longer period of time in Europe and hence the larger investment in crop improvement. The French cultivar Ariane was selected for further field trials and under optimum conditions produced crops up to approximately 1.0 m tall, yielding 1000 g/m^2 of oven dry stem (~35% bark) and 200 g/m^2 of seed (12-15% moisture content).

Key areas for future local breeding of dual purpose seed/non-textile fibre varieties are likely to resemble those reported by Scheer-Triebel (1993), namely: yield stability, yield potential and quality (seed and fibre). With regards yield stability, breeding for resistance to diseases and lodging are likely to be priorities. Lodging was a problem in the trials reported here, especially at higher seeding rates. Whilst there was no evidence of disease in any of the trials, known diseases of the current Australian linseed industry are likely to be of concern. Chief amongst these is Fusarium wilt, a vascular disease generated by a soil borne fungus (*Fusarium oxysporum*). Shortfalls in the strength of pulps produced in this study might be lessened through the breeding of cultivars with enhanced individual fibre strength

and fibre bonding strength properties (eg fibre dimensions such as wall thickness and lumen perimeter).

Flax offers a flexible crop to the Tasmanian farmer, given that it can be sown from autumn through to spring and can be grown under dryland as well as irrigated conditions. Whilst irrigation is expected to benefit most flax crops, reasonable yields of both seed and fibre can be expected from rainfed autumn sowings. This offers clear benefits in terms of spreading production over time and also geographically around the state. This is important if local fibre production is to match the requirements of the newsprint mill for reinforcing fibre, bearing in mind limitations imposed by the area of available farming land and the many crops which compete for a place in existing rotations. This flexibility, coupled with the increased financial returns and reduced risk associated with dual purpose flax cultivation, would help to counter the substantially lower fibre yields relative to hemp. Based on the figures presented in Section VI of this report, the gross margins for a dual purpose flax crop are potentially similar to those of a fibre hemp crop.

The selection of an optimum seeding rate for flax will depend on the sowing date and will involve a compromise between maximising yield and minimising potential losses from lodging. On the basis of the results presented in Chapter III.3, autumn sowings gave maximum yields at approximately 1200 plants/m^2, but were prone to lodging. The lodging was more pronounced under irrigation. A safe density for autumn sown flax (cv. Ariane) would appear to be about 1000 plants/m^2. Later sowings in winter and spring were less prone to lodge and showed stem yield gains up to approximately 1100 plants/m^2 (rainfed).

Hemp:

Under optimum conditions, the hemp cultivar Kompolti produced crops up to approximately 2.5 m tall, yielding 1500 g/m^2 of oven dry stem (~40% bark). With all imported cultivars flowering toward the end of January, it is clear that the growing season in Tasmania could accommodate much later flowering and hence potentially higher yielding genotypes. Kompolti and Kompolti Hybrid TC are reported by Meijer (1994) to have the slowest phenological development of commercially available cultivars. Later flowering landraces from Korea and Japan

were found to give much higher stem yields than these cultivars, but had very poor bark percentages. Such landraces may be of value in future breeding programmes to develop cultivars better able to utilise the relatively long Tasmanian growing season. Meijer & Keizer (1994) report that some landraces produced significantly higher stem yields than others, despite equivalent flowering times. They concluded that there was a breeding opportunity for more efficient stem dry matter accumulation and partitioning. Resistance to diseases such as Sclerotinia, Alternaria and Botrytis might be a further objective of a future breeding programme.

Studies on the response of two hemp cultivars to varying sowing dates, identified September as the optimum period for sowing hemp in Tasmania. Later sowings resulted in yield declines due to a shorter vegetative period and a reduction in light interception due to delays in canopy closure (van der Werf *et al.* 1996). The main limitation with early sowings is the sensitivity of flowering to daylength. In a controlled environment study of the flowering response of Kompolti to photoperiod, flowering was found to occur rapidly in daylengths less than about 14 hours and with increasing delay under longer days. With daylength not reaching 14 hours in Tasmania until about early November, autumn and winter sown plants accumulate the thermal time requirement (basic vegetative period + photoperiod induced phase) for flowering during a period when temperatures and particularly incident radiation are low. This results in reduced growth rates and stem yields. The potential for earlier sowing of hemp clearly depends on finding or breeding genotypes less sensitive to photoperiod. Autumn sowing might offer advantages in terms of increased yield and the possibility for dryland cropping. Furthermore, it would be possible to disperse harvesting over a longer period, thus helping to avoid bottlenecks at the processing facility. Whilst frost damage is a major limitation for early sowing of hemp in much of Europe, the low severity frosts in the main cropping regions of Tasmania are not expected to restrict production.

The irrigation trial reported in Chapter II.4, identified substantial water requirements for hemp cultivation. Whilst the rainfed treatment survived, yields were substantially below those of the irrigated treatments and would have been worse had it not been for above average rainfall figures in January. In the central and southeastern regions of Tasmania, where rainfall is significantly less and soils are less moisture retentive than at the trial site, rainfed cropping of hemp would not be viable.

The optimum plant density for hemp was found to be about 110 plants/m^2. This represented a balance between maximising the use of available resources and restricting plant losses associated with excessive competition at higher densities.

Another issue related to the future production of hemp is crop security. The trial hemp crops at Cambridge in the 1994-95 season were entered illegally on several occasions, resulting in the theft of considerable numbers of flowering heads. At the time, this was of considerable concern to the police and were it not for the deployment of security contractors, the crop would have had to be destroyed. Whilst there has been a willingness amongst government agencies to allow trial cultivation of fibre hemp, the transition to commercial cultivation would require a more comprehensive evaluation of the legal and social implications of *Cannabis* cultivation. The consensus within the relevant government agencies is that commercial cultivation would most likely be permitted if it could be demonstrated that there were significant economic benefits to the state. Production administration would most likely resemble that currently in place for the cultivation of alkaloid poppy (*Papaver somniferum*) in Tasmania. A limited number of annual licences would be issued to approved farmers stipulating the terms and conditions of cultivation. Security would consist of permanently employed field officers, working in conjunction with the police and relying on a degree of vigilance by the actual grower. A longer term solution to most of the security concerns might be the inclusion of a genetic marker in hemp, enabling it to be physically distinguished from drug varieties. Visual, olfactory and leaf shape markers have been suggested as possible characters for transformation (Begg & Buller 1995).

The low rainfall / moderate temperature conditions which normally prevail in Tasmania about the expected time of fibre harvest (January/February), are conducive to a 'dry' harvest system for fibre hemp. This system involves mowing the crop at flowering and then field drying the straw in windrows. Existing windrowers would need to be modified to accommodate the height and large biomass of the hemp crop. In the absence of a market for the core fraction, new field based decorticating machinery would be an essential component of the harvesting system. Such technology would offer substantial savings on the high transport costs associated with off-farm processing of the whole stem.

VII.3 Hemp model:

Parameters, constants and equations describing leaf area production, biomass partitioning, and pre- and post-emergence development were compiled from a number of field and controlled environment studies. These were combined with selected published parameters and constants to generate a model for predicting the growth, development and yield of hemp based on climatic, soil and management inputs.

The hemp model adequately predicted phenology, leaf area and biomass production for the cultivar Kompolti at Forthside. This represents a limited range of environments and in order to assess the broader suitability of the model, its performance will need to be assessed over a range of other site and management conditions. Improvement in the accuracy and scope of prediction are expected from the inclusion of parameters and functions relating to: soil water and nutrient availability and uptake, the contribution of non laminar sources of photosynthesis, and the influence of factors other than photoperiod on flowering.

Notwithstanding these limitations, the model has the potential to enable the results of this project to be extrapolated to other suitable production areas. By producing the hemp model within the framework of the existing APSIM (Agricultural Production System Simulator) systems model (McCown *et al.* 1996), this simulation capacity can be extended to encompass the agricultural system in which hemp is incorporated.

VII.4 Pulping potential in the newsprint industry:

Cold caustic soda pulps made from the bark fraction of hemp and flax stems were most suited to softwood kraft replacement as a reinforcing agent in newsprint manufacture. Bark pulps had excellent tear strength, however they were deficient in tensile strength and tensile energy absorption when compared to softwood kraft.

Shortfalls in the tensile strength of the bark pulp relative to kraft might be overcome by using a higher proportion of bark in the overall blend. There may also be opportunities for improvements in tensile strength through breeding and the adoption of more favourable cultural practices (Scheer-Triebel 1993).

New mill infrastructure would be required in the form of a customised CCS plant and facilities to store, handle and pre-process bales of field separated bark fibre.

Another priority for future research would be optimising fibre length reduction, both before and during pulping, to improve pulp handling properties. Significant advancements have already been made in this area with the use of extrusion pulping technology (van Roekel *et al.* 1995).

Whilst cold caustic soda core pulp is potentially suited for use as a short fibred supplement in newsprint manufacture, the properties of the core pulps are not currently in demand within the industry.

VII.5 Economic potential:

Interest from primary producers in growing hemp and flax would require that the gross margins from these crops be at least comparable with a range of crops currently being grown. The minimum bark price (mill gate) that is likely to attract farmers, would vary between flax and hemp and between growing conditions. Dual purpose flax grown under dryland conditions would require a price in the vicinity of $400/t to $450/t. Irrigated hemp and dual purpose flax grown in the more productive north west area of the state, would require a bark price in excess of about $650/t.

In the preparation of crop budgets for flax, seed sales were based on Linola, which has been recognised to have the most potential of all oilseed types (Anonymous 1992). Linola has a number of competitors for which markets are already well established, including safflower, sunflower, corn, soyabean and Canola. Because of its similarity to other oilseeds currently grown in Australia, success will depend on effective price competition with these alternatives and by taking advantage of supply shortfall periods with existing oil sources. Linola is harvested in January in southeast Australia, which fits in well with the shortage during January to March of local oil for margarine manufacture from Queeensland sunflower, safflower and corn growers. Consequently, there is potential for Linola as an import replacement product of 30000 t per annum (Anonymous 1992). As a by-product to a fibre industry, it may be possible to sell Linola seed at a more competitive price and

hence compete with existing polyunsaturated oilseeds.

Seedex Pty. Ltd. has the exclusive rights for the production, crushing and marketing of Linola, Linola oil and meal in all Australian states except Western Australia. The primary market is for pressed oil used in margarines and cooking oils (United Grain Growers 1995). Seedex Pty. Ltd. have a small crushing facility but would be unable to process the expected volume of seed produced each year from a dual purpose Linola crop. Thus, a current limitation is the availability of processing / crushing facilities. Further infrastructure in the form of a bulk seed handling facility would also be required.

Potential local end uses for the core fraction include the manufacture of particle board, bricks, marine oil spill control booms, as a short fibred supplement to eucalypt in newsprint manufacture, and as a biofuel. Use as a biofuel has been discounted on the basis that it is unlikely to generate worthwhile financial returns, given the availability of low cost alternative fuels such as wood waste and coal (L. Johnson pers. comm. 1995). The abundant supply of low cost eucalypt and recycled newsprint means that there is no current demand for alternative short fibre raw materials. The remaining options (and possibly others) require further investigation.

Interest from the newsprint industry in taking the financial risk of adopting non wood fibre crops will hinge on being able to produce a pulp with properties at least equivalent to the current imported kraft reinforcing pulp and at a price somewhat less than the imported option (L. Johnson pers. comm. 1995). The market price for kraft averaged over the period from August 1988 to March 1997 was approximately $880/t. During this period, the maximum price was $1360/t in April 1995 and the minimum was $590/t in December 1993 (Stafford 1997). The cost of producing a tonne of hemp and flax bark pulp would need to take into a account the mill gate price to farmers and the variable and fixed costs of pulping the raw material. While it is possible to estimate variable costs relating to chemical and pulping energy requirements, other costs are difficult to reliably estimate. Yield losses associated with the pulping process, and the potential need for a higher proportion of non-wood pulp in the newsprint blend (to account for strength shortfalls relative to kraft), would also need to be factored into the processing costs. Taking into account all

these considerations, kraft replacement with hemp and flax bark pulp is not financially attractive to ANM at present. Future viability would depend on a number of factors, including: fibre yield and quality improvements, elevated kraft pulp prices, and the establishment of markets (offering good prices) for the stem core fraction and the seed of flax.

References.

Angus, J.F., Cunningham, R.B., Moncur, M.W. and MacKenzie, D.H. (1981). Phasic development in field crops. 1. Thermal response in the seedling phase. Field Crops Research **3**, 365-378.

Anonymous (1992). The future potential of flax in Australia: An initial appraisal. Report prepared for the Colac Economic Development Committee by Agri-Mark Consultants Pty. Ltd. 50pp.

Anonymous (1994). Flax: All your questions answered. Booklet published by Gorham & Bateson (Agriculture) Ltd. 42pp.

Anonymous (1994a). Northern Tasmania Cash Crop Enterprise Budgets. Tasmanian Department of Primary Industry and Fisheries, November 1994.

Anonymous (1995). Cash Crop Enterprise Budgets: North West Coast. Tasmanian Department of Primary Industry and Fisheries, October 1995.

Banham P.W., Ryan K.J., Cox R.E., Russell S.L., Tascone K.L., Plummer M.K., Triffitt M.M. (1994). Refining experiments with Albury TMP, Kraft and RCF. Australian Newsprint Mills Ltd. Research Report. No. R95-7.

Banham P.W., Raymond C.A., Russell S.L., Tascone K.L., McDonald A.C., Hilder E. (1996). Massy Greene E. regnans. Australian Newsprint Mills Ltd. Research Report. No. R96-6.

Beetson B.R. & Smart W.L. (1997). Industrial hemp agronomic trials in Western Australia. Research report for Agriculture Western Australia New Industries Program. 19pp.

Begg J. & Buller C. (1995). An assessment of fibre hemp as an economic crop plant in Australia. Report for Co-operative Research Centre for Plant Science. 11pp.

Begg J. & Turner N.C. (1976). Crop water deficits. Advances in Agronomy **28**, 161-217.

Borthwick H.A. & Scully N.J. (1954). Photoperiodic responses of hemp. The Botanical Gazette. **116**, (1) 14-29.

Bosca I. (1995). Hemp breeding in Hungary; objectives, methods and results. In: Proceedings of First Bioresource Hemp Symposium, NOVA-Institute, Frankfurt, Germany, March 2-5, 627pp.

Bosia A. & Nisi D. (1977). Complete utilization of the hemp through alkali-oxygen and chemimechanical processes. In: Proceedings of 17th EUCEPA Conference, Vienna, October 1977, Paper No 7, 10 pages.

Bosia A. (1976). Pasta per carta da canapulo: pasta meccanica e pasta meccano-chimica. (Paper pulp from the woody core: mechanical pulp and chemi-mechanical pulp). Cellulosa e Carta **26**, 32-36.

Bridge B.J. & Bell M.J. (1994). Effects of cropping on the physical fertility of krasnozems. In: Proceedings of the Australian Institute of Agricultural Science Soils Ain't Soils Conference, Ulverstone, Tasmania, 5-6 September, 49-75.

Burris, J & Fehr, W.R. (1971). Methods for evaluation of soybean hypocotyl length., Crop Science **11**, 116-118.

Carberry, P.S. & Abrecht, D.G. (1990)., Germination and elongation of the hypocotyl and radicle of kenaf (*Hibiscus cannabinus*) in response to temperature. Field Crops Research, **24**, 227-240.

Carberry, P.S. & Campbell, L.C. (1989). Temperature parameters useful for modeling the germination and emergence of pearl millet. Crop Science **29**, 220-222.

Carberry P.S., Muchow R.C., Williams R., Sturtz J.D. & McCown R.L. (1992). A simulation model of kenaf for assisting fibre industry planning in Northern Australia I. General introduction and phenological model. Australian Journal of Agricultural Research **43**, 1501-13.

Carberry P.S. & Muchow R.C. (1992). A simulation model of kenaf for assisting fibre industry planning in Northern Australia. II. Leaf area development. Australian Journal of Agricultural Research **43**, 1515-26.

Carberry P.S., Muchow R.C., Hammer G.L. (1993). Modelling genotypic and environmental control of leaf area dynamics in grain sorghum. II Individual leaf level. Field Crops Research, **33**, 311-328.

Carberry P.S. (1995). Assessing the opportunity for increased production of grain legumes in the farming system - GRDC Project CSC9. A report prepared for the Grains Research and Development Corporation. 33pp.

Catling D & Grayson J. (1982). Identification of vegetable fibres. Chapman and Hall, London, 71-78.

Chilvers W.J. (1996). Managing Tasmania's Cropping Soils: A practical guide for farmers. Department of Primary Industry and Fisheries, Tasmania, Australia. 80pp.

De Groot B., van Zuilichem D.J., van der Zwan R.P. (1988). The use of non-wood fibres for pulping and papermaking in the Netherlands. In: Proceedings of First International Non-wood Fibre Pulping and Papermaking Conference, Beijing, China, July 11-14. Volume 1, 216-222.

Dempsey J.M. (1975). Hemp. In: Fiber crops. University of Florida Press, Gainesville, USA, 46-89.

Ditchfield C., Bredt J., Warner P. (1997). Whither Australian Hemp?. In: Proceedings of Second Bioresource Hemp Symposium, NOVA-Institute, Frankfurt, Germany, February 27 - March 2, 730pp.

Easson D. & Long F. (1992). The effect of time of sowing, seed rate and nitrogen level on the fibre yield and quality of flax (Linum usitatissiumum L.). Irish Journal of Agricultural and Food Research **31**, (2) 163-172.

Elliott H.G. (1959). Linen flax in Western Australia. Journal of Agriculture of Western Australia, **8**, (1) 3-14.

Fitzgerald P. (1995). Potential returns for growers, processors and investors. In: Industrial Hemp: The potential for an industrial hemp industry in Australia. Proceedings of the Industrial Hemp Conference, Melbourne, December 13-14. The Australian Institute of Agricultural Science & The Rural Industries Research and Development Corporation. 33-41.

Friederich J.C. (1964). Enkele ervaringen met de teelt van hennep. Landbouwvoorlichting **21**, (4) 145-149.

Garcia-Huidobro, J. Monteith J.L. & Squire G.R. (1982), Time, temperature and germination of pearl millet (*Pennisetum typhoides*). Journal of Experimental Botany **33** 288-296.

Gates C.T. (1955). The response of the young tomato plant to a brief period of water shortage. 1. Whole plant and principle parts. Australian Journal of Biological Science **8** 196-214.

Graham C. (1995). Capital and infrastructure requirements. In: Industrial Hemp: The potential for an industrial hemp industry in Australia. Proceedings of the Industrial Hemp Conference, Melbourne, December 13-14. The Australian Institute of Agricultural Science & The Rural Industries Research and Development Corporation. 41-51.

Green A.G. (1986). A mutant genotype of flax (*Linum usitatissimum* L.) containing very low levels of linolenic acid in its seed oil. Canadian Journal of Plant Science **66** 499-503.

Green A., Bluett C., Green R. (1994). Linola growing guide. CSIRO Division of plant Industry. 12pp.

Green A.G. & Marshall D.R. (1984). Isolation of induced mutants in linseed (*Linum usitatissimum* L.) having reduced linolenic acid content. Euphytica **33**, 321-328.

Grenikov A.S. & Tollochko T. (1953). Cultivation of hemp (In Russian). Moscow USSR: State Editors of Agricultural Literature. 447pp.

Guleria W., Singh C. (1983). Effects of cultural practices on growth, yield and economics of fibre flax production in the north western Himalayas. Experimental Agriculture **19** 87-90.

Haberlandt F. (1879). Der algemeine landwirtschaftliche Pflanzenbau. (General agricultural crop production) Wein.

Hackett C. (1991). Mobilising environmental information about lesser known plants: the value of two neglected levels of description. Agroforestry Systems **14** 131-143.

Hadley P., Roberts E.H., Summerfield R.J. and Minchin F.R. (1984). Effects of temperature and photoperiod on flowering in soybean (*Glycine max* L. Merrill): a quantitative model. Annals of Botany **53**, 669-681.

Hague J. and Goodwin A. (1996). Assessment of the suitability of UK grown non-wood fibres for paper making. In: Proceedings of the Pira International Conference, Uses for non-wood fibres - commercial and practical issues for papermaking. Peterborough, England, 29-30 October. 1-15.

Hansen H.V. (1945). Flax production in Southern Tasmania. The Tasmanian Journal of Agriculture **16**, (2) 43-45.

Harper F. (1983). Principles of arable crop production. Granada Publishing Ltd. 336pp.

Hatfield, J.L. & Egli, D.B. (1974), Effect of temperature on the rate of soyabean hypocotyl elongation and field emergence. Crop Science **14**, 423-426.

Heslop Harrison J. & Heslop Harrison Y. (1969). Cannabis sativa L. In: The Induction of flowering. Some case studies. (Ed. L.T. Evans), MacMillan Co. Pty. Ltd. 205-226.

Heslop Harrison J. & Heslop Harrison Y. (1972). Sexuality of Angiosperms. In: Physiology of development: from seeds to sexuality. (Ed. F.C. Steward). Academic Press, New York. 13-289.

Heuser O. (1927). Hanf und Hartfaser. Julius Springer Verlag, Berlin 156pp.

Holliday R. (1960). Plant population and crop yield. Field Crop Abstracts. **13** 159-167 and 247-254.

Jakobey I. (1965). Experiments to produce hemp with fine fibres. Novenytermeles **14** (1), 145-149.

Jeyasingam J.T. (1991). Mill experience in the application of non-wood fibre for paper making. In: Nonwood plant fiber pulping progress report No. 20, Technical Association of the Pulp & Paper Industry (TAPPI), 39-44.

Jones, C.A. & Kiniry, J.R. (1986). CERES-maize: A simulation model of maize growth and development. Texas A & M University Press, College Station, USA, 194pp.

Judt M. (1992). Nonwood fibres: not just a niche. Pulp and Paper International, **34** (8), 45-47

Kirby R.H. (1963). Chapter III: Mulberry Family (Moraceae). In: Vegetable Fibres: Botany, Cultivation & Utilisation. World Crop Series, Interscience Publishers Incorporated, New York, 46-62.

Kundu B.C. (1942). The anatomy of two Indian fibre plants, *Cannabis* and *Corchorus* with special reference to fibre distribution and development. Indian Botany Society Journal. **21** 93-128.

Kwon B., Park H., Lee J., Son E., Hwrang J. (1989). Response of flax varieties to planting density. Korean Journal of Crop Science **34** (3), 225-228.

Lafond G. (1993). The effects of nitrogen, row spacing and seeding rate on the yield of flax under a zero till production system. Canadian Journal of Plant Science. **73**, (2) 375-382.

Landsberg J.J. (1977). Some useful equations for biological studies. Experimental Agriculture **13**, 273-286.

Leeper G.W. & Uren N.C. (1993). Soil Science: An Introduction. Melbourne University Press. 300pp.

Lips S.J. (1993). Thermomechanical pulp from fibre hemp. In: Proceedings of 18th EUCEPA International Mechanical Pulping Conference, Oslo, Norway, June 15-17. 625pp.

Lolicato S., Bluett C., Blackstock J. (1996). Low THC Indian hemp (Cannabis sativa) trials in Victoria. Paper presented at First Australian New Crops Conference, University of Queensland, Gatton College, July 1996. 9pp.

Loomis R.S. & Connor D.J. (1992). Crop Ecology: Productivity and management in agricultural systems. Cambridge University Press. 538 pp.

Low I. (1995). UK Hemp Production. In: Proceedings of First Bioresource Hemp Symposium, NOVA-Institute, Frankfurt, Germany, March 2-5, 627pp.

Ludlow M.M. (1975). Environmental and biological control of photosynthesis (R Marcelle, ed). Junk, The Hague, 123-134.

Maas, S.J. & Arkin, G.F. (1978). Users guide to SORGF: A dynamic grain sorghum growth model with feedback capacity. Temple Blackland Res. Cent. Progr. Model Doc. No. 78-1.

Maddern KN. (1993). Assessment of the second crop of non-resinous Indian hemp grown in Tasmania. APPM Research and Technology Report, No. 93/40.

Maddern K.N. & French J. (1994). The potential application of non-wood fibres in papermaking - An Australian perspective. In: Proceedings of 1994 APPITA Conference, Melbourne, Australia, 177-185.

Maeyer E.A.A. de. & Huisman W. (1994). New Technology to harvest and store fibre hemp for paper pulp. Journal of the International Hemp Association. **1** (2), 38-40.

Major D.J. (1980). Photoperiod response characteristics controlling flowering of nine crop species. Canadian Journal of Plant Science **60** (3),777-784.

Major D.J., Hanna M.R., Beasley B.W. (1991). Photoperiod response characteristics of alfalfa (*Medicago sativa L.*) cultivars. Canadian Journal of Plant Science **71** 87-93.

Major D.J., Rood S.B., Miller F.R. (1990). Temperature and photoperiod effects mediated by the sorghum maturity genes. Crop Science **30**, 305-310.

McCown R.L., Hammer G.L., Hargreaves J.N.G, Holzworth D.P. & Freebairn D.M. (1996). APSIM: A novel software system for model development, model testing and simulation in agricultural systems research. Agricultural Systems **50**, 255-271.

McDougal G.J., Morrison I.M., Stewart D., Weyers J.D.B., Hillman J.R. (1993). Plant fibres: Botany, chemistry and processing for industrial use. Journal of the Science of Food and Agriculture **62**, 1-20.

McGovern J.N., Coffelt D.E., Hurter A.M., Ahuja N.K., Wiedermann A. (1987). Chapter 9: Other Fibres. In: Pulp and Paper Manufacture, Volume 3: Secondary Fibres and Non-Wood Pulping. Published by The Joint Textbook Committee of the Paper Industry (TAPPI/CPPA), Canada and USA. 266pp.

McKenzie A.W. (1994). A guide to pulp evaluation. CSIRO Publications. 66pp.

Meijer E.P.M. de (1994). Variation of *Cannabis* with reference to stem quality for paper pulp production. Industrial Crops and Products **3** (3), 201-211.

Meijer E.P.M. de & Keizer L.C.P. (1994). Variation for *Cannabis* for phenological development and stem elongation in relation to stem production. Field Crops Research **38** (1), 37-46.

Meijer E.D.M. de, van der Kamp H.J., van Eeuwijk F.A. (1992). Characterisation of *Cannabis* accessions with regard to cannabinoid content in relation to other plant characters. Euphytica **62**, 187-200.

Meijer W.J.M., van der Werf H.M.G., Mathijssen E.W.J.M., van den Brink P.W.M. (1995). Constraints to dry matter production in fibre hemp (*Cannabis sativa* L) European Journal of Agronomy, **4** (1), 109-117.

Meijer E.P.M. de. (1995). Fibre hemp cultivars: A survey of origin, ancestry, availability and brief agronomic characteristics. Journal of International Hemp Association **2** (2), 66-73.

Meinke H., Carberry P.S., Keating B.A., Freebairn D.M., Turpin J. and Dimes J. (1996). APSIM and its use in cropping system analysis. Paper presented at CAMASE workshop: "Rotation models for ecological farming", Wageningen, The Netherlands, 15-16 April.

Muchow R.C. & Wood I.M. (1980). Yield and growth responses of kenaf (*Hibiscus cannabinus* L) in a semi-arid tropical environment to irrigation regimes based on leaf water potential. Irrigation Science **1**, 209-222.

Muchow R.C. & Carberry P.S. (1989). Environmental control of phenology and leaf growth in a tropically-adapted maize. Field Crops Research **20**, 221-36.

Muchow R.C. and Carberry P.S. (1990). Phenology and leaf area development in a tropical grain sorghum. Field Crops Research **23**, 221-37.

Nelson C.H. (1944). Growth responses to hemp to differential soil and air temperatures. Plant Physiology **19**, 294-309.

Ng T.T., Wilson J.R., Ludlow M.M. (1975). The influence of water stress on water relations and growth of a tropical (C4) grass, *Panicum maximum* var. *trichoglume*. Australian Journal of Plant Physiology, **2**, 581-595.

Ong, C.K. & Monteith, J.L. (1985). Response of pearl millet to light and temperature. Field Crops Research, **11**, 141-159.

Pate D.W. (1994). Chemical ecology of *Cannabis*. Journal of International Hemp Association **1** (2), 29-37.

Probert M.E., Dimes J.P., Keating B.A., Dalal R.C., Strong W.M. (1997). APSIM's water and nitrogen modules and simulation of the dynamics of water and nitrogen in fallow systems. Agricultural Systems (in press).

Ratkowsky D. (1983). Non-linear regression modelling - A unified practical approach. Marcel Dekker New York. 276pp.

Reed K.L., Hamerly E.R., Dinger R.F. & Jarvis P.G. (1976). Journal of Applied Ecology **13**, 925.

Reichert G. (1994). Government of Canada Report on Hemp. Bi-weekly Bulletin, 7 (23), 7pp.

Rivoira G. and Marras G.F. (1975). La canapa per l'industria cartaria: aspetti e problemi della tecnica colturale. Cellulosa e Carta **26** (12), 9-24.

Rowland G. (1980). An agronomic evaluation of fibre flax in Saskatchewan. Canadian Journal of Plant Science **60**, 55-59.

Salisbury F.B. and Ross C.W. (1985). The Photosynthesis-Transpiration Compromise. In: Plant Physiology. Wadsworth Publishing Company. 540pp.

Scheer-Triebel M. (1993). Breeding of short fibre flax for industrial use. Paper presented at 3rd Regional Workshop on Flax, Bonn, Germany, 15-17 June, 1993. 12pp.

Selkirk S.W. (1996). Comparison of industrial hemp with hardwood plantations for fibre production on ex-potato land in the Ballarat region. Project report for School of Forestry and Resource Conservation, University of Melbourne, 39pp.

Senchenko G.I. & Timonin M.A. (1978). Komoplya (Hemp). Kolos, Moskva, 285pp.

Shinozaki K. & Kira T. (1956). Intraspecific competition among higher plants. Logistic theory of the C-D effect. J. Inst. Polytech. Osaka City University. D7, 35-72.

Stafford B. (Ed.). (1997). Price Watch: Pulp, Paper and Board. Ausnewz Pulp and Paper. **11**, (3) 11.

Tamm, E. (1933). Further investigations on the germination and the emergence of agricultural crop plants. Pflanzenbau **10**, 297-313.

Tanner C.B. & Sinclair T.R. (1983). Efficient water use in crop production: Research or re-search?. In: Limitations to Efficient Water Use in Crop Production (Eds. H.M. Taylor, W.R. Jordan & T.R.Sinclair), American Society of Agronomy, Madison, WI, 1-27.

Tilt J. (1941). Flax experimental work. Results of 1940-41 season's trials. The Tasmanian Journal of Agriculture **12**, (3) 77-81.

Tschaneff K. (1959). Der Hanfbau in Bulgarien. Fibra **4**, 59-67..

Turner, J. (1987). Linseed Law. A handbook for growers and advisors. BASF United Kingdom Limited. 356pp.

United Grain Growers. (1995). Linola Link Brochure, April 1995. 4pp.

Valder G. (1893). Notes on experiments with hemp (*Cannabis sativa*) in New South Wales. The Agricultural Gazette of New South Wales. **4**, (12) 907-910.

Van Dam J.E.G. (1995). Potentials of hemp as industrial fibre crop. In: Proceedings of First Bioresource Hemp Symposium, NOVA-Institute, Frankfurt, Germany, March 2-5, 627pp.

Van der Werf H.M.G. (1991). Agronomy and crop physiology of fibre hemp. A literature review. CABO (Centre for Agrobiological Research, Wageningen, The Netherlands) Report 142, March 1991, 16pp.

Van der Werf H. (1994). Crop Physiology of Fibre Hemp (*Cannabis sativa* L.). Doctoral thesis, University of Wageningen. 153pp.

Van der Werf H.M.G., Haasken H.J., Wijlhuizen M. (1994). The effect of daylength on yield and quality of fibre hemp (*Cannabis sativa L.*). European Joumal of Agronomy **3**, (2) 117-123.

Van der Werf, H., Brouwer, K., Wijlhuizen, H., Withagen, J.C.M. (1995). The effect of temperature on leaf appearance and canopy establishment in fibre hemp (*Cannabis sativa* L.), Annals Applied Biology **126**, 551-561.

Van der Werf H., Wijlhuizen M., De Schutter J. (1995a). Plant density and self thinning affect yield and quality of fibre hemp (*Cannabis sativa* L.) Field Crops Research **40** 153-164.

Van der Werf H.M.G., Mathijssen E.W.J.M., Haverkort A.J. (1996). The potential of hemp (*Cannabis sativa* L.) for sustainable fibre production: crop physiological appraisal. Annals of Applied Biology **129**, 109-123.

Van der Werf H.M.G. 1997. The effect of plant density on light interception in hemp (*Cannabis sativa* L.). Journal of the International Hemp Association **4** (1), 8-13.

Van Roekel G.J. (1994). Chemimechanical pulping of fibre hemp. In: Proceedings of First Bioresource Hemp Symposium, NOVA-Institute, Frankfurt, Germany, March 2-5, 627pp.

Van Roekel G.J., Lips S.J.J., Op de Kamp R.G.M., Baron G. (1995). Extrusion pulping of true hemp bark fibre (*Cannabis sativa L.*) In: Proceedings of 1995 Tappi Pulping Conference, Chicago, October 1-5, 945pp.

Warrington, I.J. & Kanemasu, E.T. (1983). Corn growth response to temperature and photoperiod: 1. Seedling emergence, tassel initiation and anthesis. Agronomy Journal **75**, 749-754.

Weller D. (1987). A re-evaluation of the -3/2 power rule of plant self thinning. Ecological monographs **57**, 281-321.

Willey R. & Heath S. (1969). The quantitative relationships between plant population and crop yield. Adv. Agron. **21**, 281-321.

Wilson R.W. (1944). Flax production. The Tasmanian Journal of Agriculture, **15** (4), 108-109.

Wong A., Krzywanski R., Chiu C. (1993). Agriculture-based pulp as secondary papermaking fibres. In: Proceedings of 1995 Tappi Pulping Conference, Chicago, October 1-5, 945pp.

Wong A., Chiu C. 1995. Pulping and bleaching of hemp (*Cannabis sativa*). In: Proceedings of 1993 Tappi Pulping Conference, Atlanta, Georgia, November 1-3, 1250pp.

Young J. 1992. Canadian nonwood pulp mill to start up in early 1993. Pulp and Paper, September 1992, 144-145.

Zhang M & Nie X. (1992). Papermaking characteristics of the flax whole stalk bleached pulps. In: Proceedings of Second International Nonwood Fibre Pulping and Papermaking Conference, 6-9 April, Shanghai, China, 1992. Volume 2: 825-833.

Appendix V.1a: Bark pulping results for cv. Kompolti.
Properties are based upon conditioned basis weight.

Sample type	Applied %NaOH	Freeness (ml)	Drainage time (sec)	Specific refining energy (kWhr/t)	Average fibre length (mm)	Handsheet %o.d. content	Bulk (cm^3/g)	Tear index (mNm^2/g)	+/-95% confidence interval
Lampen Mill									
+4.75mm fraction	6.0	415			1.7	91.2	1.60	32.20	5.42
+2.36mm fraction	6.0	381			1.6	91.5	1.50	23.96	2.48
+1.18mm fraction	6.0	476			1.8	90.5	1.61	16.16	1.62
+300um fraction	6.0	297			1.5	90.5	1.47	9.74	0.44
12-1CP refiner									
hb1/1	5.3	700		73		92.7	2.11	29.60	2.97
hb2/1	5.2	440		791		93.8	1.80	32.00	1.53
hb1/2	5.3	419		665		92.7	1.81	38.30	4.97
hb2/2	5.2	58		2565		93.8	1.52	19.10	1.52
hb8/2	10.2	44	83	3366		92.3	1.54	27.90	2.19
hb7/2	12.8	172	20	871		92.2	1.62	28.30	3.79
hb8/1	10.2	272		988		92.5	1.69	34.90	2.92
hb7/1	12.8	428	6	631		91.9	1.80	33.60	3.54
hb6/1	10.0	662				92.8	2.01	31.23	2.18
hb9/1-tmp	0.0	434		701		92.7	2.28	29.79	6.62
hb9/2-tmp	0.0	165	33	1628		92.1	1.94	25.18	2.28
hb9/3-tmp	0.0	66	139	2745		92.7	1.82	19.97	0.73
hb10/1-low s.c.%	3.8	358		1377		88.2	1.81	15.32	4.29
hb10/2-low s.c.%	3.8	36	152	3036		96.2	1.61	26.90	3.50
Small screen									
hb11/1	10.0	575		1479		82.3	1.98	28.54	3.35
hb11/2	10.0	460		646		96.3	1.70	31.96	7.23
hb11/3	10.0	325		303		92.3	1.71	33.24	3.02
hb12	13.3	412		474		89.3	1.76	21.37	1.40
hb12-bleached (2%)	13.3	399		474		94.7	1.80	21.19	2.07

Tensile energy absorption (J/g)	Tensile index (Nm/g)	+/-95% confidence interval	Burst index (kPa m^2/g)	PPS roughness (um)	PPS porosity (ml/min)	Light scattering coefficient (cm^2/g)	ISO brightness	L *	a *	b *
0.69	46.40	3.29	3.17	6.84	515	203	42.1	78.8	1.0	15.0
0.64	46.57	4.84	3.44	6.93	218	172	43.1	79.6	1.0	15.1
0.47	38.15	3.80	2.41	6.71	462	175	38.2	77.2	1.7	17.1
0.51	41.53	5.08	2.20	6.84	175	171	39.1	77.3	1.5	16.0
0.31	20.76	3.15	1.59	10.17	10000	169	37.3	76.2	2.0	16.0
1.03	41.70	2.50	3.43	7.49	781	239				
0.83	36.80	5.58	3.31	7.35	2773	209	39.2	77.2	1.9	15.5
1.25	50.85	5.30	3.53	7.46	5	206				
1.51	48.10	5.36	4.42	7.81	4	285				
1.16	41.50	2.24	3.60	7.21	47	252				
1.11	39.40	3.23	3.24	7.23	194	249	43.5	80.2	1.7	15.6
1.07	37.10	2.37	3.18	7.20	757	244	40.4	77.6	2.3	14.7
0.68	28.66	2.63	2.17	8.55	10000	239	38.9	76.6	2.3	14.6
0.45	23.77	3.40	1.84	10.74	1025	216	37.9	75.7	1.8	14.4
0.80	39.67	6.27	2.78	9.00	31	198				
0.63	43.26	7.93	2.87	4.58	5	239				
0.37	27.84	5.25	2.39	7.89	78	193	41.1	78.4	1.8	15.3
0.52	40.20	8.22	2.78	6.34	0	127	32.9	72.7	2.5	16.0
0.58	25.87	5.64	2.33	8.94	3312	250				
0.85	33.89	4.41	2.59	6.60	3559	246				
0.76	34.27	2.64	2.81	6.63	295	248				
0.59	29.40	1.15	1.96	7.40	1419	213				
0.55	29.52	1.54	1.29	8.34	1781	216				

Appendix V.1b: Core and whole stem pulping results for cv. Kompolti.
Properties are based upon conditioned basis weight.

Sample type	Applied %NaOH	Freeness (ml)	Drainage time (sec)	Specific refining energy (kWhr/t)	Average fibre length (mm)	Handsheet %o.d. content	Bulk (cm^3/g)	Tear index (mNm^2/g)	+/-95% confidence interval
Core pulping:									
hc4/1	10.2	237		576	0.6	91.9	1.44	2.99	0.09
hc4/2	10.2	127		1048	0.5	90.0	1.22	2.52	0.06
hc4/3	10.2	99		1710	0.5	93.9	1.19	2.63	0.33
hc5/1	5.2	216		888	0.5	92.2	2.24	2.92	0.10
hc5/2	5.2	102		1594	0.5	92.6	2.04	2.94	0.37
hc5/1-bleached (2%)	6.4	198		888	0.5	91.8	1.88	3.11	0.22
hc5/2-bleached (2%)	6.4	105		1594	0.5	92.7	1.74	2.81	0.19
hc1/2	4.6	138		1802	0.6	89.8	2.02	3.00	0.14
hc1/3	4.6	69		2593	0.5	89.8	1.80	2.81	0.36
hc2/1-tmp	0.0	168		4435	0.5	89.7	2.68	1.54	0.07
hc2/2-tmp	0.0	72		5843	0.5	89.8	3.05	1.47	0.08
hc3/1	10.2	100		1299	0.5	90.2	1.23	2.87	0.26
hc3/2	10.2	100		2664	0.4	89.8	1.09	2.45	0.30
Whole stem pulping									
bc1/1-tmp	0.0	121		2700	1.1	91.1	3.72	6.26	0.58
bc1/1-tmp screened	0.0	76		2700		90.3	2.74	8.62	0.27
bc2/1	10.1	647		51		91.1	1.90	12.22	1.18
bc2/2	10.1	311	8	742		91.1	1.64	14.41	0.79
bc2/3	10.1	182	12	1241		91.2	1.53	13.84	1.54
bc2/4	10.1	65	65	2168		89.1	1.41	12.45	0.86
bc3/1	5.0	456	3	479		89.9	2.03	10.09	1.57
bc3/2	5.0	224	12	875		90.1	1.78	9.85	0.43
bc3/2-bleached (2%)	5.0	207		875		89.3	1.81	10.50	1.03
bc3/3	5.0	136	16	1223		90.8	1.66	9.22	0.25
bc3/4	5.0	69	34	1635		90.0	1.56	7.90	0.82

Tensile energy absorption (J/g)	Tensile index (Nm/g)	+/-95% confidence interval (kPa	Burst index m^2/g)	PPS roughness (um)	PPS porosity (ml/min)	Light scattering coefficient (cm^2/g)	ISO brightness	L *	a *	b *
0.45	52.21	3.94	2.10	3.39	37	296	35.8	79.7	2.1	24.8
0.48	60.01	5.08	3.07	3.05	3	227	34.4	78.5	2.3	24.8
0.63	68.10	3.90	3.45	2.59	2	242	33.3	77.8	2.4	25.0
0.17	25.44	1.60	0.93	5.67	583	422				
0.30	36.28	1.51	1.37	5.52	73	438	46.1	82.9	1.6	17.6
0.22	30.98	0.80	1.09	5.01	168	404	64.2	91.3	-1.9	14.1
0.39	42.11	1.28	1.55	4.16	39	394	63.1	91.1	-1.8	14.9
0.34	38.87	2.11	1.45	4.55	127	487	47.7	82.7	1.7	15.2
0.53	48.05	2.11	1.88	3.94	33	498	45.9	81.6	1.8	15.3
0.06	11.38	0.00	0.00	6.14	1652	617	48.6	82.1	2.1	12.9
0.10	15.59	0.63	0.44	5.30	658	667	49.3	82.3	2.1	12.4
0.62	62.82	9.19	2.83	2.95	3	257				
0.47	60.66	5.00	3.96	2.66	0	172				
0.14	12.97	2.30	0.96	11.79	1319	362	38.2	75.8	2.7	14.2
0.25	21.65	1.90	1.09	7.84	183	409				
0.24	19.24	1.06	0.94	8.15	9999	213	39.4	81.7	2.0	23.6
0.51	37.78	1.89	1.82	6.94	211	241	36.0	77.9	2.8	21.1
0.53	43.67	2.48	2.07	6.34	15	265	36.4	79.7	2.4	24.1
0.50	46.83	2.74	2.54	5.84	4	222	34.9	78.8	2.6	24.3
0.13	20.30	1.62	0.67	6.96	1116	255	46.8	83.7	1.2	18.4
0.22	30.85	2.47	1.25	6.25	34	261	45.0	82.9	1.0	19.1
0.21	30.27	4.09	1.94	6.23	71	260				
0.26	36.65	1.93	1.31	6.82	16	269	43.7	82.4	1.1	19.7
0.31	40.43	3.46	1.65	6.02	5	247	42.0	81.3	1.2	19.8

Appendix V.1c: Pulping results for cv. Ariane.
Properties are based upon conditioned basis weight.

Sample type	Applied %NaOH	Freeness (ml)	Drainage time (sec)	Specific refining energy (kWhr/t)	Average fibre length (mm)	Handsheet %o.d. content	Bulk (cm^3/g)	Tear index (mNm^2/g)	+/-95% confidence interval
Core pulping									
fc1/1		108	58	798		89.7	1.88	5.35	0.37
fc1/2		55		1093		89.7	1.61	4.85	0.38
Bark pulping									
fb1/1		480	5	270		90.9	1.98	28.48	2.43
fb1/2		251	16	652		90.1	1.76	27.83	3.60
fb1/3		160	31	1035		91.4	1.60	25.87	1.91
fbl 1		231			1.2	91.5	1.28	8.33	0.21
fbl 2		395			2.4	92.0	1.35	21.20	3.52
fbl 3		246			1.7	92.6	1.25	10.30	0.49
fbl 4		232			1.9	92.3	1.26	12.40	0.87
Whole stem pulping									
fw1/1		151	29	453		89.2	1.95	14.21	2.76
fw1/2		86	45	801		89.2	1.60	10.50	1.53
fw1/3		38		1395		88.8	1.59	8.33	1.37

Tensile energy absorption (J/g)	Tensile index (Nm/g)	+/-95% confidence interval	Burst index (kPa m^2/g)	PPS roughness (um)	PPS porosity (ml/min)	Light scattering coefficient (cm^2/g)	ISO brightness	L *	a *	b *
0.13	26.76	0.96	0.92	6.55	76	234	29.0	78.2	2.1	32.2
0.21	34.65	2.29	1.19	6.09	20	219	29.0	77.7	1.9	31.4
0.55	24.08	1.79	1.95	9.14	1968	196	30.7	78.3	2.4	29.7
0.73	30.04	4.12	2.42	8.43	159	168	28.3	77.3	2.8	31.9
1.09	38.13	4.59	3.22	9.69	20	202	27.4	76.5	2.8	31.6
0.77	51.30	5.89	3.24	5.89	67	126				
0.97	55.60	6.25	5.37	6.25	148	113				
0.84	58.80	5.94	4.48	5.94	13	111				
1.11	61.80	5.99	4.78	5.99	20	117				
0.20	25.30	1.46	1.09	8.53	222	161	49.1	85.1	0.8	18.0
0.21	26.32	1.52	1.51	7.09	23	167	46.8	84.8	0.8	20.0
0.28	40.94	7.72	1.51	7.19	2	156	45.3	84.3	0.9	21.1

Appendix V.2a: Results from hemp bleaching trials

	%H2O2	%NaOH	ISO Bright.	L *	a *	b *
Bark						
hb7/2	0	0.0	40.9	78.3	2.3	15.4
	2	0.8	67.4	91.8	-0.5	11.6
	2	1.2	65.4	91.0	-0.2	11.9
bast	0	0.0	38.6	75.6	1.9	13.8
	1	0.4	60.1	87.8	-0.2	11.2
	1	0.8	60.8	88.2	-0.1	11.3
	2	0.4	64.4	89.0	-0.4	10.0
	2	0.8	64.9	89.4	-0.4	9.8
	2	1.2	63.0	88.9	-0.2	10.4
	3	0.4	66.1	90.0	-0.5	9.7
	3	0.8	67.5	90.6	-0.6	9.5
hb12	0	0.0	42.9	80.5	1.8	17.0
	1	0.2	60.4	90.0	-0.5	15.2
	1	0.4	61.4	90.3	-0.4	14.9
	1	0.6	62.3	91.9	-1.0	13.1
	1	0.8	61.1	89.9	-0.3	14.3
	2	0.2	66.2	90.5	-0.5	14.2
	2	0.4	65.3	91.6	-1.1	13.4
	2	0.6	67.5	92.2	-0.9	12.5
	2	0.8	66.9	91.8	-1.0	12.3
	3	0.4	69.1	92.7	-1.3	12.0
	3	0.6	68.6	92.4	-1.3	11.9
	1.5	0.8	65.4	91.4	-0.7	12.8
	3	1.0	69.2	92.4	-1.0	11.3
Core						
hc5/1	0	0.0	48.1	83.9	1.5	17.1
	1	0.4	59.6	90.3	-0.5	16.8
	1	0.8	60.3	90.6	-0.7	16.5
	1	1.2	59.2	90.2	-0.5	16.8
	1	1.6	58.0	89.6	-0.3	16.8
	1	2.0	56.6	88.9	-0.1	17.2
	2	0.8	64.2	92.1	-1.1	15.5
	2	1.2	64.8	92.1	-1.2	15.0
	2	1.6	64.4	91.9	-1.1	14.9
	2	2.0	62.0	91.1	-1.0	15.8
	2	2.4	61.1	90.7	-0.8	15.9
	3	1.2	65.0	92.3	-1.4	15.2
	3	1.6	65.0	92.2	-1.3	15.0
	1.5	2.0	59.2	90.1	-0.7	16.7
	3	2.4	64.6	91.8	-1.2	14.6
	3	2.8	62.5	91.7	-1.0	15.4
Whole stem						
bc3/2	0	0.0	48.9	84.8	0.8	18.2
	2	0.4	66.7	92.8	-1.5	14.4
	2	0.8	68.4	93.2	-1.6	13.5
	2	1.2	67.3	92.4	-1.4	13.5
	2	1.6	65.0	91.8	-1.2	14.0
	3	0.4	69.9	93.7	-1.9	13.1
	3	0.8	70.9	93.6	-1.8	12.4
	3	1.2	70.1	93.1	-1.8	12.2
	3	1.6	67.7	92.3	-1.5	12.8

Appendix V.2b: Results from flax bleaching trials

	%H2O2	%NaOH	ISO Bright.	L *	a *	b *
Bark						
fb1/2	2	0.0	48.1	85.7	0.9	19.7
	2	0.2	66.2	92.3	-1.8	14.1
	2	0.4	68.0	93.1	-1.8	13.2
	2	0.6	67.9	92.7	-1.9	13.0
	2	0.8	67.5	92.2	-1.8	12.0
	2	1.0	68.8	92.0	-1.9	12.0
Core						
fc1/2	2	0.0	30.1	79.9	1.8	33.9
	2	0.4	49.6	90.2	2.2	26.9
	2	0.8	50.9	90.1	-2.0	25.5
	2	1.2	53.0	90.4	-1.7	23.9
	2	1.6	52.2	89.9	-1.3	23.7
	2	2.0	52.1	89.7	-1.2	23.5
Whole						
fw1/2	2	0.0	31.4	79.8	2.2	31.9
	2	0.2	40.5	84.2	-0.4	28.5
	2	0.4	43.3	86.1	-1.0	27.3
	2	0.6	44.6	86.3	-1.1	26.7
	2	0.8	45.1	87.2	-1.0	26.9
	2	1.0	44.7	86.9	-0.8	26.8